System Modeling Techniques for PRA P-200

January 2009

United States
Nuclear Regulatory Commission

P-200 - System Modeling Techniques for PRA

January 2009 – Bethesda, MD

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Course Outline

Tuesday - AM
0. Introduction (8)
1. Basics (16)
2. Fault Trees (32)

Tuesday - PM
FT Practice examples
3. System Models (26)
Workshop (Appendix A)

Wednesday – AM
4. Uncertainties (19)
5. Event Trees (17)
    practice example
6. Sequence Models (17)
    practice example

Wednesday – PM
7. Common Cause Failure Models (35)
Workshops – ET & Sequence Logic (cutsets)

Thursday – AM
8. Quantifying Logic Models (28)
9. Data Analysis (14)
10. Human Error Modeling (19)
11. Results (16)

Thursday - PM
Workshops – Cutsets, Quant., and CCF

Friday – AM
12. Special Topics (21)
Questions/Review
Exam

Course Objectives

- Build PRA modeling and analysis skills
  - Event tree and fault tree model development
  - Dependent failures and common cause modeling
  - Component failure mechanisms
- Improve understanding of quantification process
- Improve ability to extract key results from a PRA
- Greater familiarity with PRA goals and process
- Aleatory (stochastic) versus Epistemic (state of knowledge) uncertainty

Required Background

- Elementary probability theory
- Probability distribution functions
- Fault Tree basics
- Cut sets
- Event trees
- Boolean Algebra

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1. U.S. Nuclear Regulatory Commission, Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (NUREG-75/014), 1975.
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8. G. Apostolakis and S. Kaplan, "Pitfalls in Risk Calculations," Reliability Engineering, 2, 135-145 (1981).
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10. U.S. NRC, A Review of NRC Staff Uses of Probabilistic Risk Assessment, NUREG-1489, 1994.
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14. A. Mosleh, D. Rasmuson, and F. Marshall, Guidelines on Modeling Common-Cause Failures in PRA, NUREG/CR-5485, 1998.
15. F. Marshall, D. Rasmuson, and A. Mosleh, Common Cause Failures Parameter Estimations, NUREG/CR-5497, 1998.
16. ASME, Addenda to ASME RA-S-2002 Standard for Probabilistic Risk Assessment for Nuclear Power Plant Applications, ASME RA-Sb-2005, December 30, 2005.
17. ANS, External-Events PRA Methodology, ANSI/ANS-58.21-2007, March 1, 2007.

Acronyms

A	Availability
AFW	Auxiliary Feedwater
AOV	Air Operated Valve
APB	Accident Progression Bins
APET	Accident Progression Event Tree
AUTO	Automatic reactor trip
CCF	Common Cause Failures
CCW	Component Cooling Water
CV	Check Valve
DG	Diesel Generator
ECI	Emergency Coolant Injection
ECR	Emergency Coolant Recirculation
EDG	Emergency Diesel Generator
ET	Event Tree
F	Unreliability
FT	Fault Tree
FTR	Fail To Run
FTS	Fail To Start
HRA	Human Reliability Analysis
IE	Initiating Event
λ	Failure rate
LOCA	Loss of Coolant Accident
LOP	Loss of Power
LOSP	Loss of Off-Site Power
LPI	Low Pressure Injection
LPR	Low Pressure Recirculation
LT	Long Term
MACCS	MELCOR Accident Consequence Code System
MAN	Manual reactor trip
MDP	Motor Driven Pump
MOV	Motor Operated Valve
NPP	Nuclear Power Plant
P	Probability
P&ID	Piping and Instrumentation Diagram
PCS	Power Conversion System
PDS	Plant Damage State
PORV	Power-Operated Relief Valve
PRA	Probabilistic Risk Assessment
Q	Probability (of failure)
R	Reliability
Rx	Reactor
SIS	Safety Injection Signal
SLOCA	Small break LOCA
ST	Short Term
T&M	Testing and Maintenance
t	time
Tr	Train
Trans	Transient initiating event

System Modeling Techniques for PRA

Lecture 1 - PRA Basics

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Objective

- Review of basic concepts of PRA
- Review basic structure of a PRA

- Section Outline
  - Risk
  - System models for PRA
  - Probability vs. Frequency
  - Reliability vs. Availability
  - PRA structure for nuclear power plants
  - Elements of Level 1 PRA

Some Common Terms

- Conservative versus Non-Conservative
- Cutsets
  - Minimal and Non-Minimal
- Core Damage and Large Early Release
- PRA and PSA
- Accident Sequence versus Accident Scenario
- Complimented Events

Definition of Risk

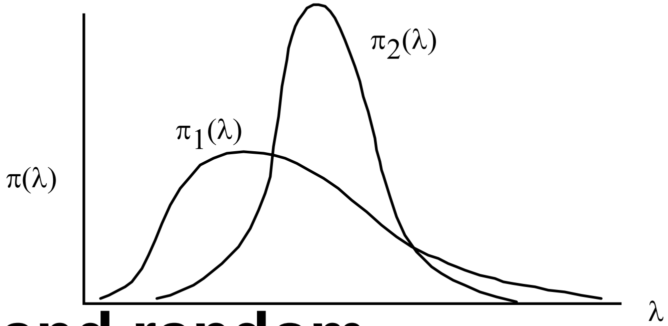
- **Formal (vector) definition used in NPP PRA (risk triplet):**
  - **Risk = {scenario$_i$, probability$_i$, consequences$_i$}**
    - **Multiple scenarios contribute to risk**
    - **Consequence can be a vector**
      - **e.g., different health effects (early fatalities, latent cancers, etc.)**
- **Commonly used scalar form:**
  - **Risk = probability x consequences (CDP)**

or = frequency x consequences (CDF)

“Scenario” Defined in Terms of Cut Sets

- A *cut set* is a combination of events that cause the “top event” to occur
  - Top Event = Core Damage (consequence)
- Minimal cut set is the smallest combination of events that causes to top event to occur
- Each cut set represents a failure scenario that must be “ORed” together with all other cut sets for the top event when calculating the total probability of the top event

Probability of Frequency Formalism



- **Aleatory Uncertainty**
  - **Also known as stochastic and random uncertainty**
  - **Irreducible, given model of world**
  - **Characterized by (assumed) model parameters**
- **Epistemic Uncertainty**
  - **Also known as state-of-knowledge uncertainty**
  - **Reduces as data accumulates**
  - **Quantified by probability distributions**

Common PRA Models

- Uncertainty in occurrence time of event - aleatory
  - Binomial
    - P{r failures in N trials |ϕ } = $\frac{N!}{r!(N-r)!} \phi^r (1-\phi)^{N-r}$
    - Probability of failure for a single demand
      - P{1 failure in 1 trial | ϕ } = ϕ
  - Poisson
    - P{r failures in (0,T) | λ } = $\frac{(\lambda T)^r}{r!} e^{-\lambda T}$
    - Probability of one or more failures => Exponential
      - $P\{T_f < t \mid \lambda\} = 1 - e^{-\lambda t} \approx \lambda t$ (for small λt)

        Note that P(1 or more failures) = 1 – P(zero failures)
- Uncertainty in rate of occurrence (i.e., on λ and ϕ) - epistemic
  - Lognormal
  - Other (e.g., Gamma, Beta, Maximum Entropy)

Probability and Frequency

- **Probability**
  - **Internal measure of certainty about the truth of a proposition**
  - **Always conditional**
  - **Unitless**
  - **Value between zero and 1.**
  - **Used for all events in a PRA except the initiating event**
- **Frequency**
  - **Parameter used in model for aleatory uncertainty**
  - **Units of per-demand or per-unit-of-time**
  - **Time-based frequencies can be any positive value (i.e., can be greater than one)**
  - **Only used for initiating events and failure rates**
- **Different concepts; sometimes numerically equal**

Probability and Frequency Example

- **Frequencies (failure rates)**
  - **$1x10^{-3}$ failures/demand (binomial)**
  - **$1x10^{-4}$ failures/operating hours (Poisson)**
- **Frequencies converted to probabilities based on a specified mission (i.e., probability of successfully completing mission)**
  - **P(pump fails to start on demand)**
    - **P{1 failure |1 demand} = $\left(\frac{1!}{1!0!}\right) (10^{-3})^1(1-10^{-3})^0 =10^{-3}$**
  - **P{pump fails to run for 24 hrs.}**
  - **P{failure time < 24 hrs} = $1-e^{-(1E-4)(24)}$ = 2.4E-3**

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Reliability (R)

- **Dictionary Definition:**
  - **Reliability ~ dependability, trustworthiness, repeatability**
- **Reliability Engineering/PRA Usage:**
  - **Reliability = Probability a component or system performs its intended function adequately over a given time interval, i.e., for a mission time t**

    $$R(t) = P\{T_f > t\}$$

    where T_f is the time to failure

    - **In other words, likelihood that component survives past mission time**

Reliability (R)

- **Note:**
  - **Reliability is a formal, quantitative measure**
  - **Concept does not address repair of component/system**
  - **Unreliability: $F(t) = 1 - R(t)$**

Availability (A)

- Dictionary Definition
  - Availability ~ state of being capable for use in accomplishing a purpose
- Reliability Engineering/PRA Usage
  - Availability = Probability a component or system is able to perform its intended function at a given point in time, i.e.,
  - $A(t) = P\{X(t) = 1\}$
    - where:
      - $X(t) = 1$, component is “good”
      - $X(t) = 0$, component is “failed”

Availability (A)

- **Note:**
  - **Concept allows for repair of component/system**
  - **Unavailability: $Q(t) = 1 - A(t)$**
  - **Average unavailability:**

$$Q_{ave} = \frac{1}{T}\int_0^T Q(t)\,dt$$

Common Pitfall

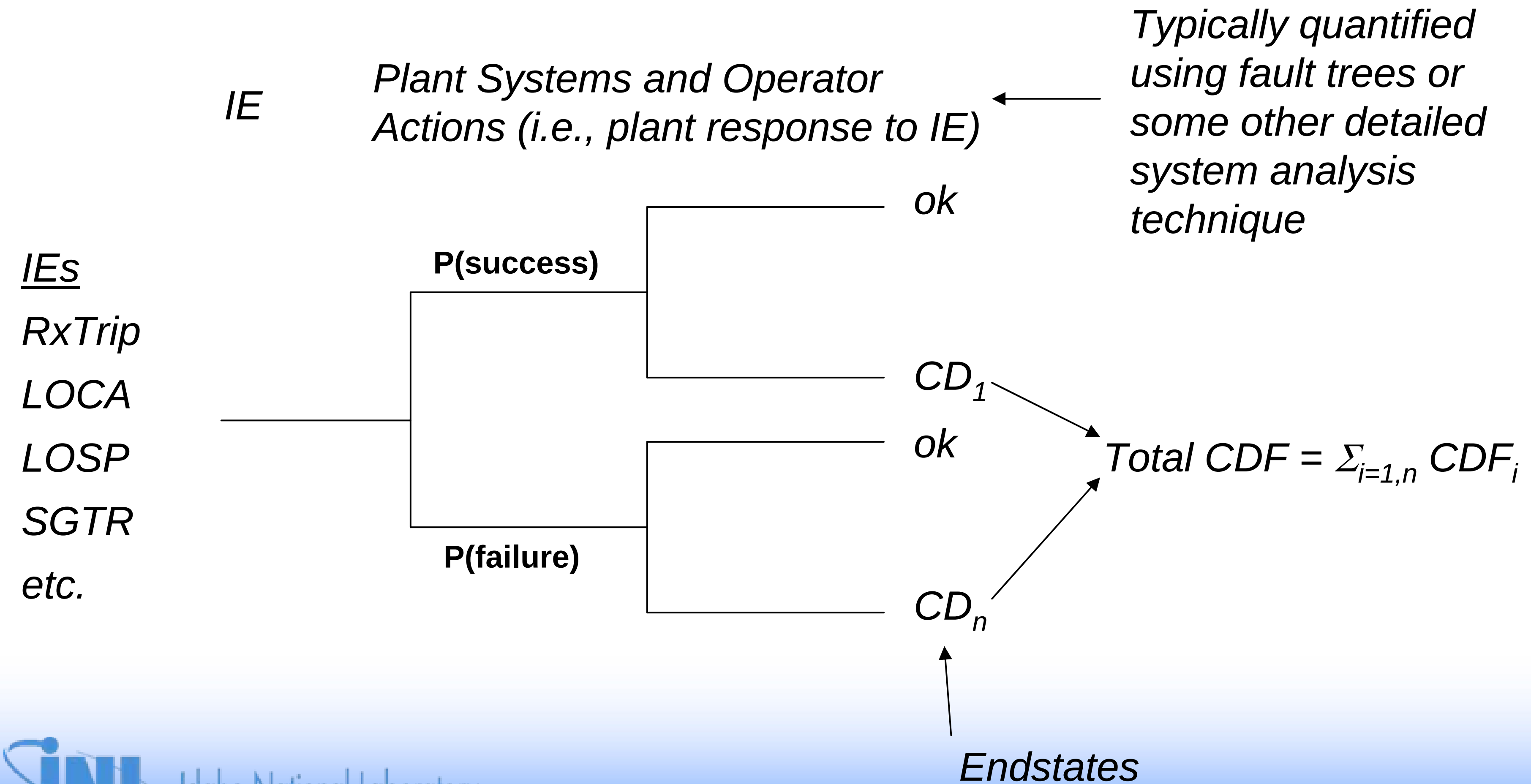
- **Confusion of frequency and probability**
  - **Example: SLOCA and subsequent LOSP**

$$\lambda_{SLOCA\ \&\ LOSP} \neq \lambda_{SLOCA} \times \lambda_{LOSP}$$

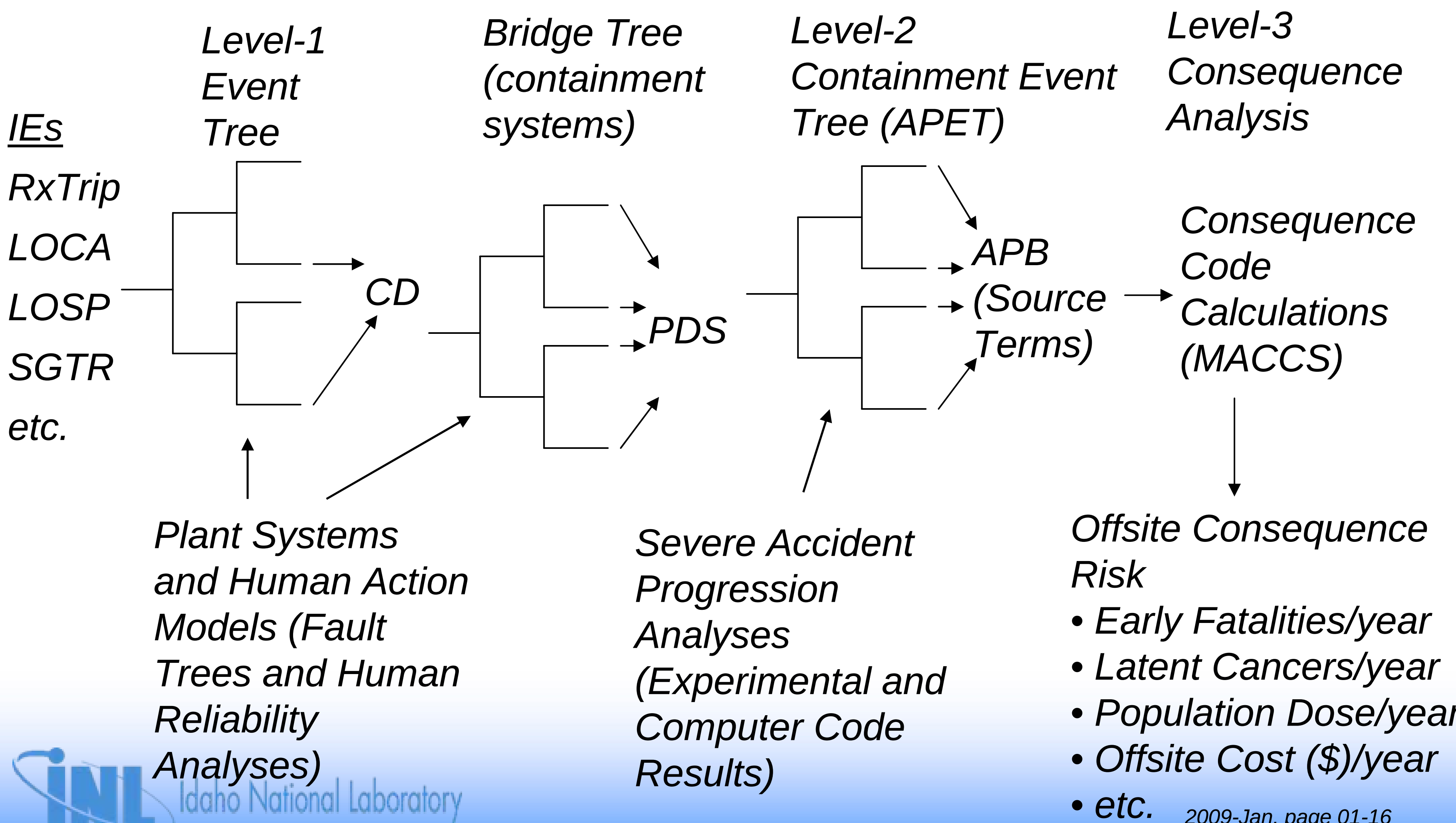
If λ_{SLOCA} = 1E-3/year and λ_{LOSP} = 1E-2/year

What is: frequency of SLOCA and subsequent LOSP?

Level-1 PRA (Internal Events Analysis)



Overview of Level-1/2/3 PRA



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Lecture 2 - Fault Trees

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Objectives

- Review of fault tree basics
- Develop understanding of:
  - When to use fault trees
  - Construction techniques
  - How to solve fault trees
  - How to quantify fault trees

Outline

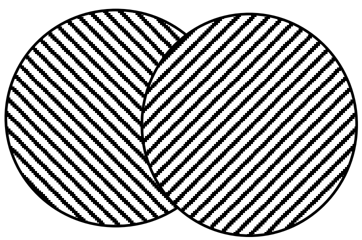
- Boolean Algebra
- Basic Elements of a Fault Tree
- When to use a Fault Tree Model
- Cut sets
- Fault Tree construction
- Cut set generation

Basic Probability Concepts Used in PRAs

$A \cup B$

A or B

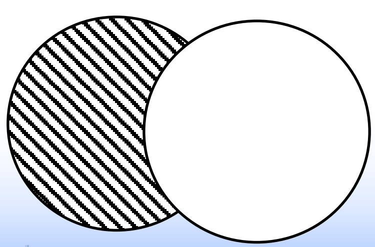
$A + B$



$A \cap /B$

A and /B

$A * /B$



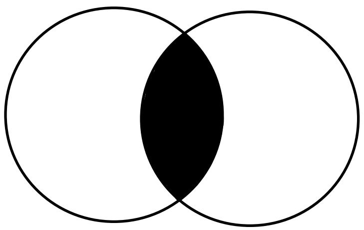
Complemented Event (B does not fail)

Venn Diagrams

$A \cap B$

A and B

$A * B$

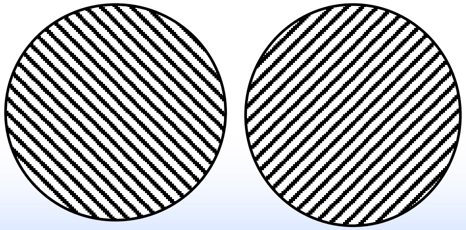


$A \cup B$

A or B

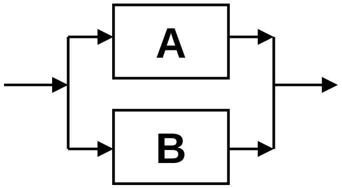
$A + B$

when the events are mutually exclusive

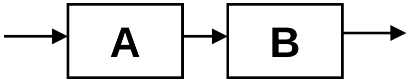


Simple FT logic illustration

- Two components in parallel (redundant)
  - Both need to fail to fail the system
  - P(system failure) = P(A) * P(B)



- Two components in series
  - Any one failure, fails the system
  - P(system failure) = P(A) + P(B)



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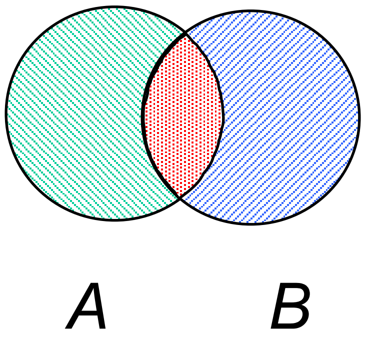
Summing Probabilities

- **Need to account for the overlap of the two events**
- **P(A+B) = P(A) + P(B) – P(AB)**



Rules of Boolean Algebra

Mathematical Symbolism	Engineering Symbolism		Designation
(1a) $X \cap Y = Y \cap X$	$X * Y = Y * X$	Algebra	Commutative Law
(1b) $X \cup Y = Y \cup X$	$X + Y = Y + X$		
(2a) $X \cap (Y \cap Z) = (X \cap Y) \cap Z$	$X * (Y * Z) = (X * Y) * Z$ $X(YZ) = (XY)Z$		Associative Law
(2b) $X \cup (Y \cup Z) = (X \cup Y) \cup Z$	$X + (Y + Z) = (X + Y) + Z$		
(3a) $X \cap (Y \cup Z) = (X \cap Y) \cup (X \cap Z)$	$X * (Y + Z) = (X * Y) + (X * Z)$ $X(Y+Z) = XY + XZ$		Distributive Law
(3b) $X \cup (Y \cap Z) = (X \cup Y) \cap (X \cup Z)$	$X + (Y * Z) = (X + Y) * (X + Z)$		
(4a) $X \cap X = X$	**Important!** $X * X = X$	Important During Cut Set Generation	Idempotent Law
(4b) $X \cup X = X$	$X + X = X$		
(5a) $X \cap (X \cup Y) = X$	$X * (X + Y) = X$		Law of Absorption
(5b) $X \cup (X \cap Y) = X$	$X + X * Y = X$		
(6a) $X \cap X' = \Phi = 0$	$X * /X = \Phi = 0$		Complementation
(6b) $X \cup X' = \Omega = I$	$X + /X = \Omega = I$		
(6c) $(X')' = X$	$/(/X) = X$		
(7a) $(X \cap Y)' = X' \cup Y'$	$/(X * Y) = /X + /Y$		DeMorgan's Theorem
(7b) $(X \cup Y)' = X' \cap Y'$	$/(X + Y) = /X * /Y$		

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Boolean Algebra Exercises

Simplify:

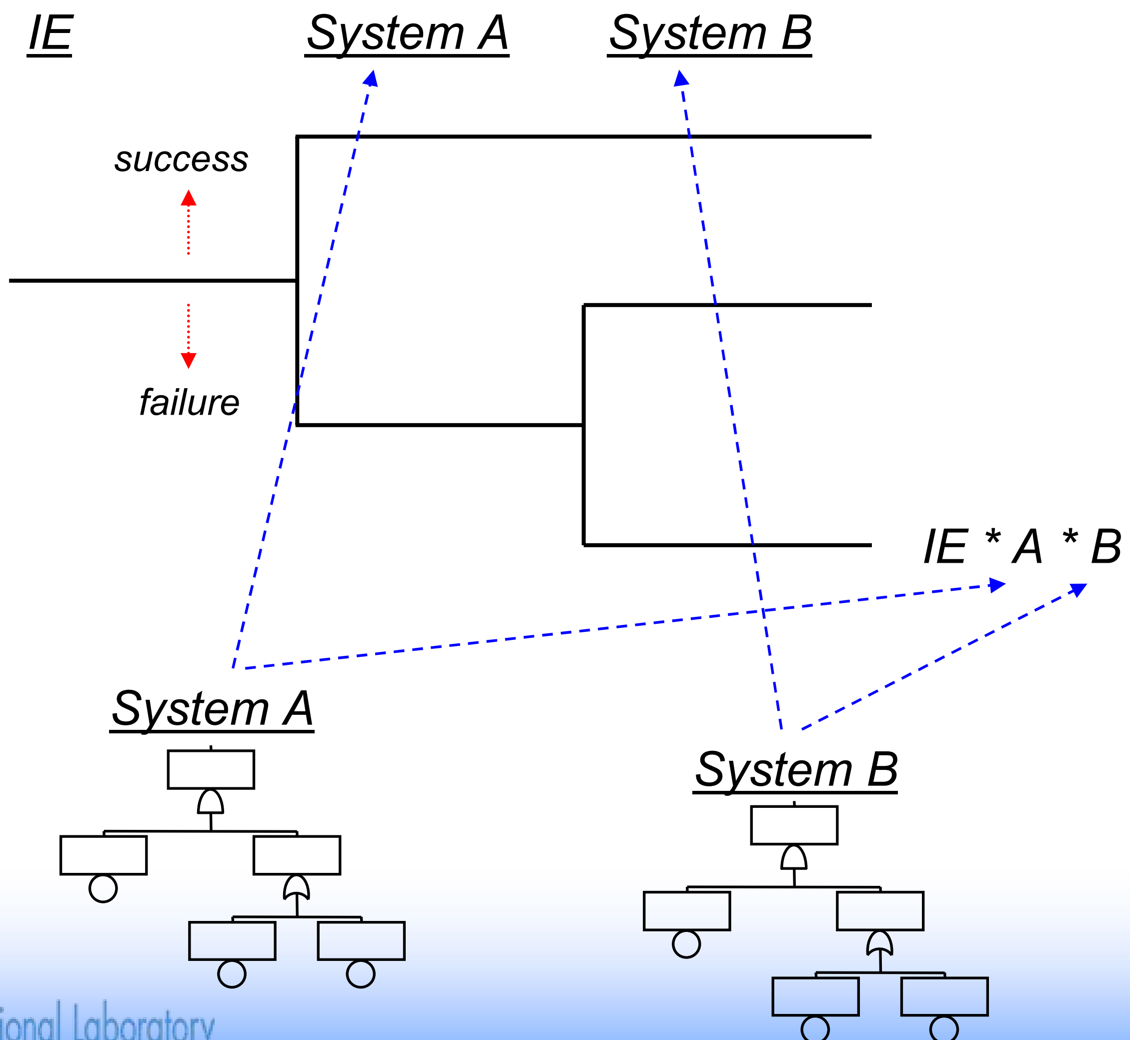
T1 = (A + B) * (B + C).

T2 = (D + E) * (/D + E).

Fault Trees and Event Trees

- Basic modeling tools in PRA
- Event Tree used for “high-level” sequence of events
  - Typically (but not necessarily) chronological
- Most high-level events on ET modeled in detail using fault trees
  - Fault trees often referred to as “system” models

FT & ET in PRA



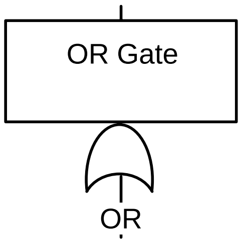
Method Selection

- Consider *event trees* when:
  - Interested in *consequences* of an initiating event
    - Inductive reasoning
  - Multiple barriers, sequential challenges
  - Multiple outcomes of interest
  - Process-oriented users
- Consider *fault trees* when:
  - Interested in *causes* of an event
    - Deductive reasoning
  - Single top event of interest

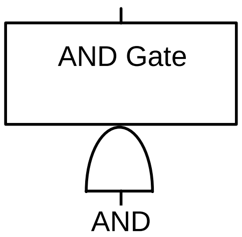
Method Selection (cont.)

- **Consider other methods (e.g., analytical methods, Markov models, dynamic event trees, direct simulation) when:**
  - **Time dependence is important**
  - **Process dynamics strongly affect sequence development and likelihood**

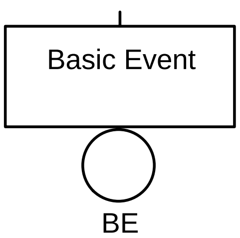
Basic Fault Tree Symbols



OR Gate – logic gate that implies any of the inputs is sufficient to produce an output (i.e., propagate up through the gate). The probability of an output from this gate is the sum of the probabilities of all the inputs to this gate.

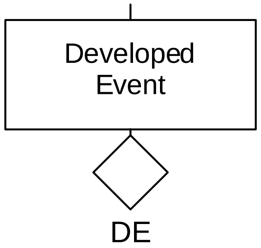


AND Gate – logic gate that implies all of the inputs must occur for the output to occur. The probability of an output from this gate is the product of the probabilities of all of the inputs to this gate.

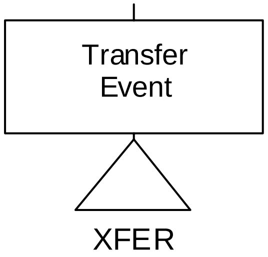


Basic Event – identifies the lowest (most basic) type of event in the fault tree. There is no further development (i.e., fault tree logic) below a basic event beyond assigning the basic event probability (by the analyst).

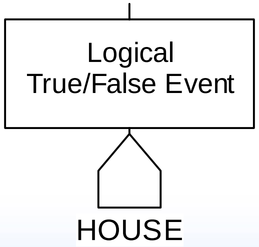
Basic Fault Tree Symbols (cont.)



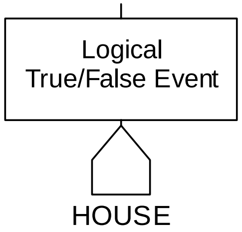
Developed Event – Sometimes called an Undeveloped Event. This is a basic event that is developed elsewhere. That is, in the PRA it is represented as just a probability, no logic.



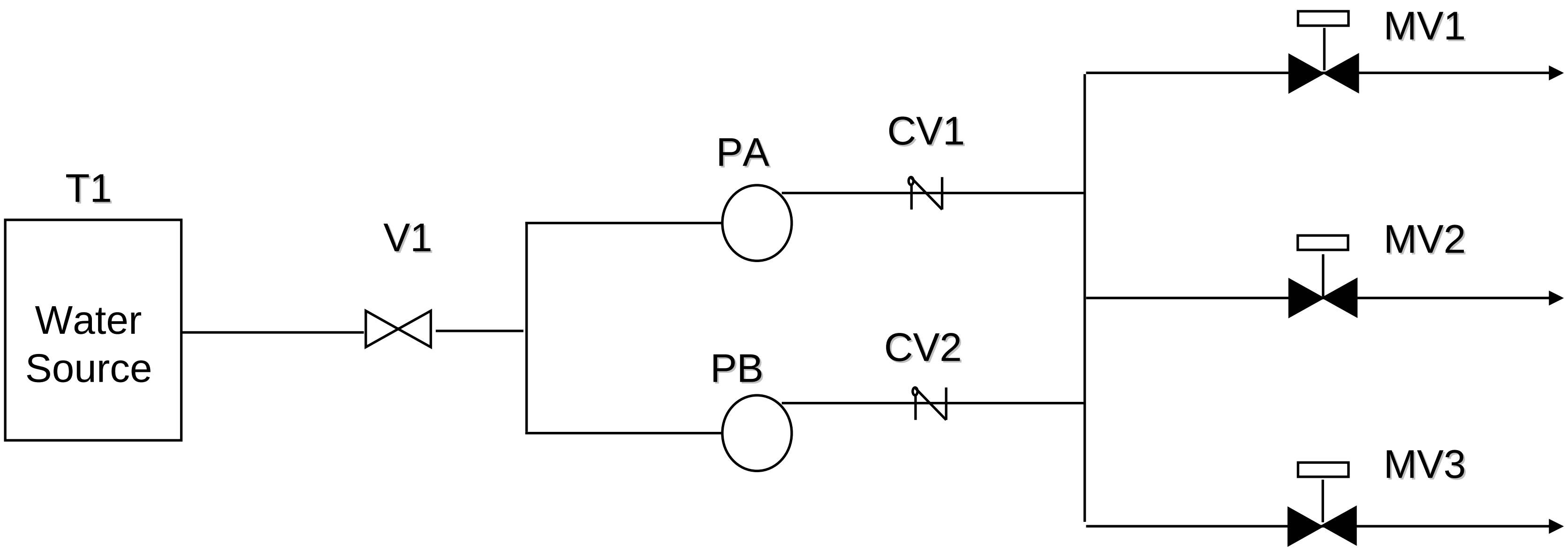
Transfer Event – Symbol used to show there is additional logic under this event, but that logic is developed elsewhere in the PRA. Sometimes used to account for support system dependencies (i.e., the support system fault tree exists in the PRA, but is not explicitly reproduced every time it is needed).



House Event – Logical True (or False) event in the fault tree logic. Note that this is different from just setting an event probability to 1 or zero.


Logical
True/False Event
HOUSE

Example Cut Sets - ECI



***Success Criteria**: Flow from any one pump through any one MV*

T_ tank

V_ manual valve, normally open

PS-_ pipe segment

P_ pump

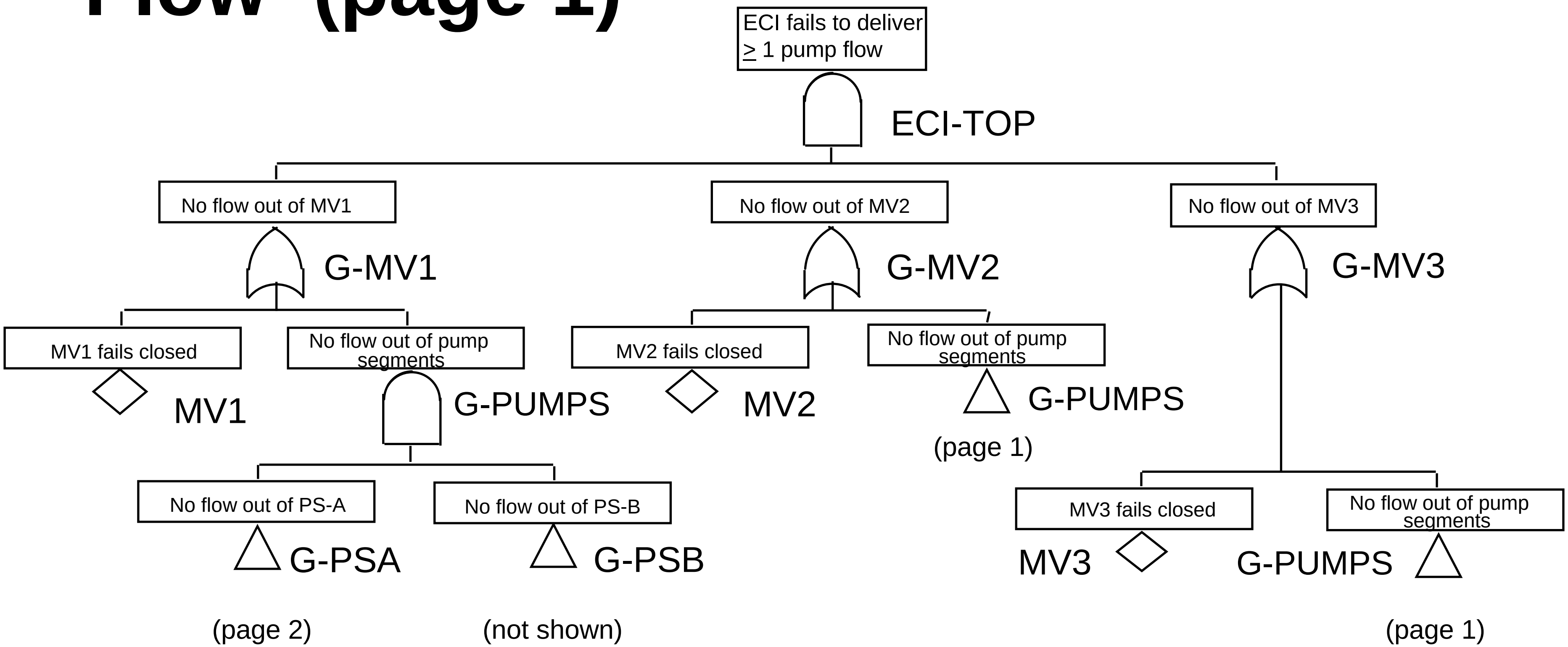
CV_ check valve

MV_ motor-operated valve, normally closed

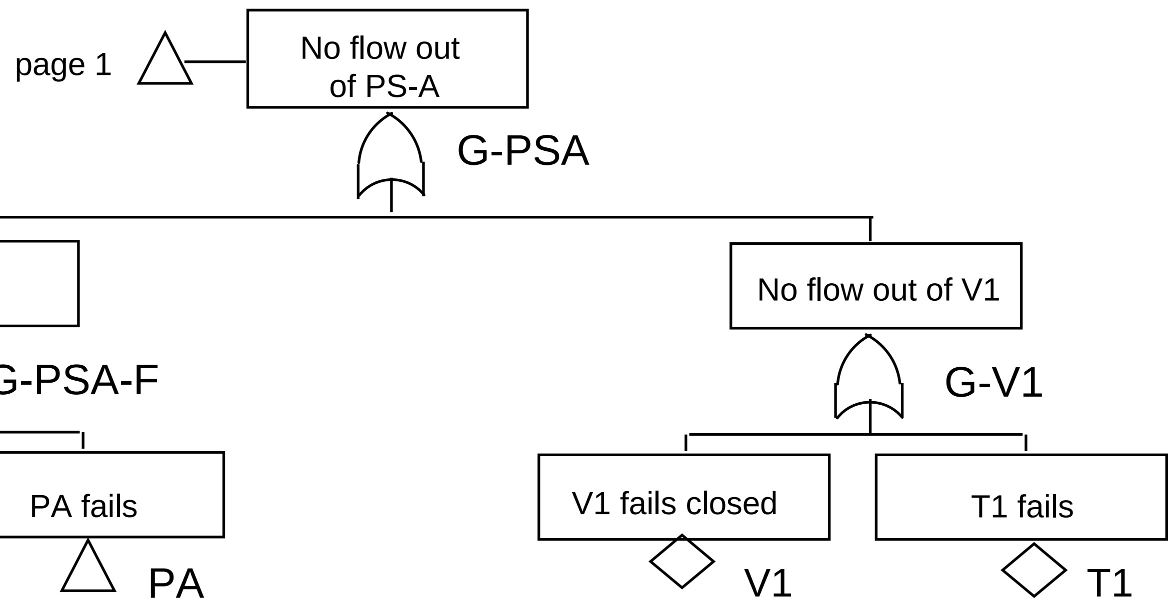
Two Common Fault Tree Construction Approaches

- "Sink to source"
  - Start with system output (i.e., system sink)
  - Modularize system into a set of pipe segments (i.e., group of components in series)
  - Follow reverse flow-path of system developing fault tree model as the system is traced
- Block diagram-based
  - Modularize system into a set of subsystem blocks
  - Develop high-level fault tree logic based on subsystem block logic (i.e., blocks configured in series or parallel)
  - Expand logic for each block

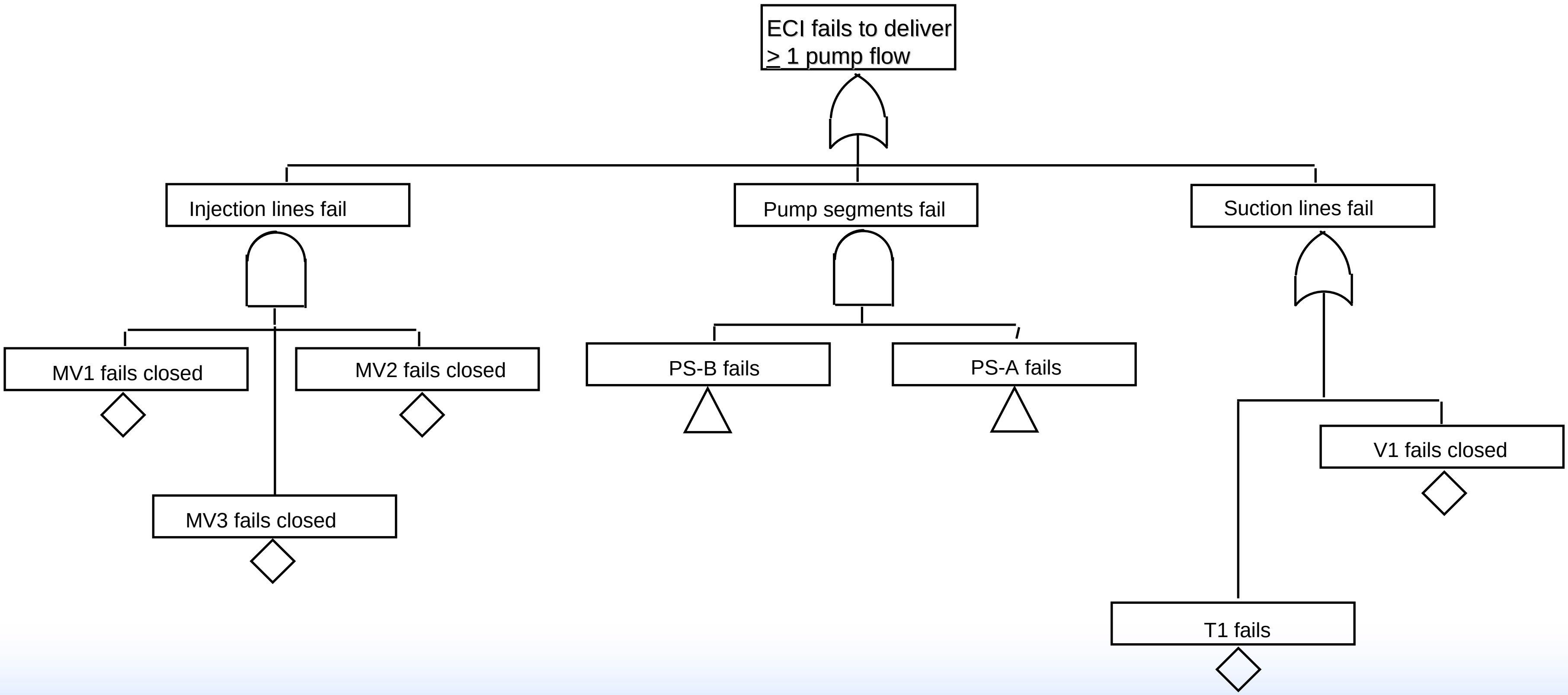
ECI System Fault Tree - Reverse Flow (page 1)



ECI System Fault Tree (page 2)



ECI System Fault Tree (block diagram method)



Cut Sets by Boolean Expansion of Fault Tree

ECI-TOP = G-MV1 * G-MV2 * G-MV3.

Start Substituting

ECI-TOP = (MV1 + G-PUMPS) * (MV2 + G-PUMPS) * (MV3 + G-PUMPS)

ECI-TOP = (MV1 * MV2 * MV3) +
(MV1 * MV2 * G-PUMPS) +
(MV1 * G-PUMPS * MV3) +
(MV1 * G-PUMPS * G-PUMPS) +
(G-PUMPS * MV2 * MV3) +
(G-PUMPS * MV2 * G-PUMPS) +
(G-PUMPS * G-PUMPS * MV3) +
(G-PUMPS * G-PUMPS * G-PUMPS).

Keep substituting and Performing Boolean Algebra (e.g., X*X = X)

ECI-TOP = (MV1 * MV2 * MV3) +
(MV1 * MV2 * G-PUMPS) +
(MV1 * G-PUMPS * MV3) +
(MV1 * G-PUMPS) +
(G-PUMPS * MV2 * MV3) +
(G-PUMPS * MV2) +
(G-PUMPS * MV3) +
(G-PUMPS).

ECI-TOP = (MV1 * MV2 * MV3) +
(G-PUMPS).

Cut Sets (cont.)

ECI-TOP = (MV1 * MV2 * MV3) +
(G-PSA * G-PSB).

ECI-TOP = (MV1 * MV2 * MV3) +
((G-PSA-F + G-V1) * (G-PSB-F + G-V1)).

ECI-TOP = (MV1 * MV2 * MV3) +
(G-PSA-F * G-PSB-F) +
(G-PSA-F * G-V1) +
(G-V1 * G-PSB-F) +
(G-V1).

ECI-TOP = (MV1 * MV2 * MV3) +
(G-PSA-F * G-PSB-F) +
(G-V1).

ECI-TOP = (MV1 * MV2 * MV3) +
(PA + CV1) * (PB + CV2) +
(V1 + T1).

ECI-TOP = MV1 * MV2 * MV3 +
PA * PB +
PA * CV2 +
CV1 * PB +
CV1 * CV2 +
V1 +
T1.

Specific Failure Modes Modeled for Each Component

- **Each component associated with a specific set of failure modes/mechanisms determined by:**
  - **Type of component**
    - **E.g., Motor-driven pump, air-operated valve**
  - **Normal/Standby state**
    - **Normally not running (standby), normally open**
  - **Failed/Safe state**
    - **Failed if not running, or success requires valve to stay open**

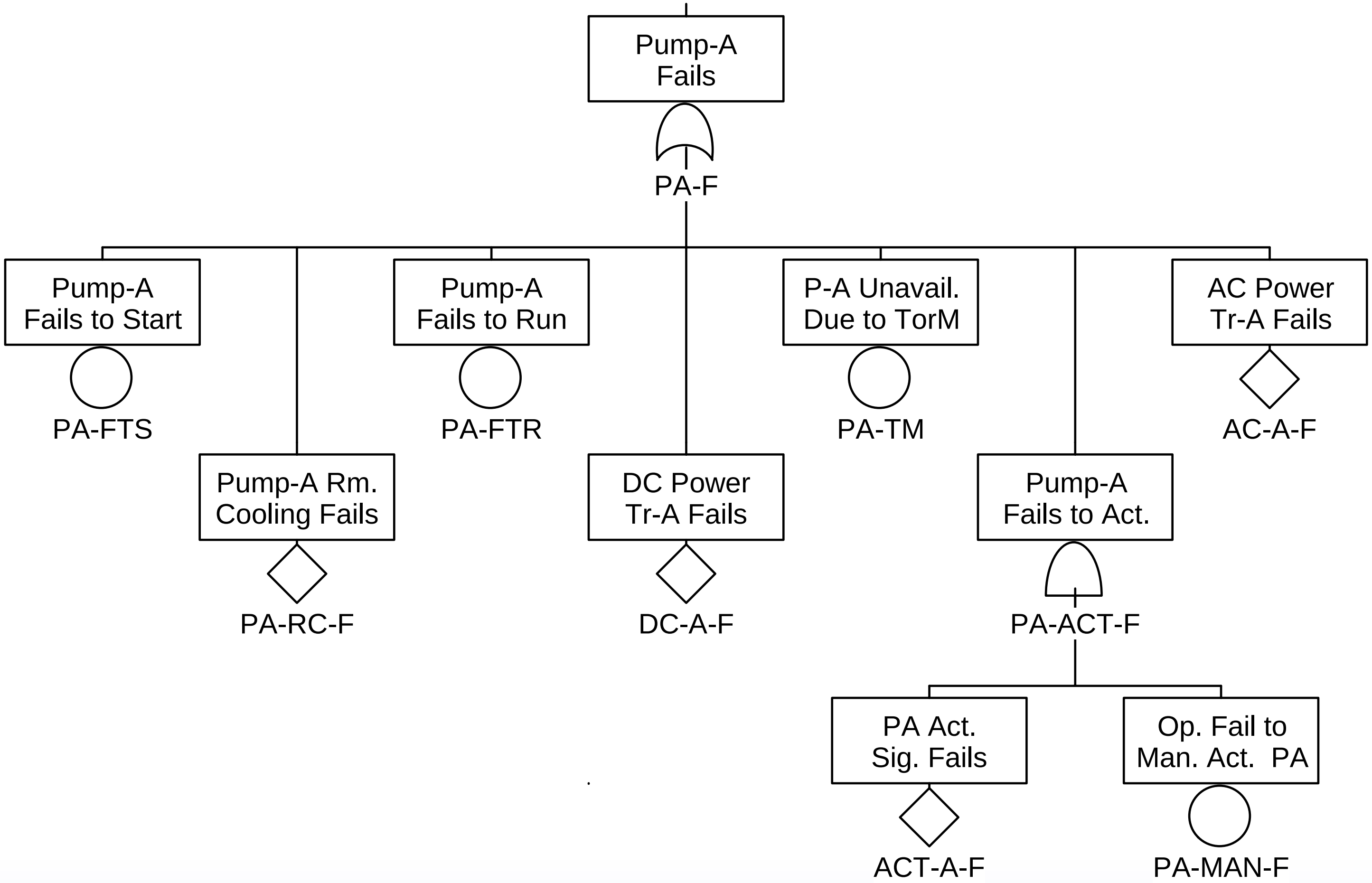
Typical Component Failure Modes

- Active Components
  - Fail to Start
  - Fail to Run
  - Unavailable because of Test or Maintenance
  - Fail to Open/Close/Operate
  - Definitions not always consistent among PRAs
    - e.g., transition from start phase to run phase can be defined differently

Typical Component Failure Modes (cont.)

- **Passive Components (Not always modeled in PRAs)**
  - **Rupture**
  - **Plugging (e.g., strainers/orifice)**
  - **Fail to Remain Open/Closed (e.g., manual valve)**
  - **Short (cables)**

Example FT for Pump



Component Boundaries

- Typically include all items unique to a specific component, e.g.,
  - Drivers for EDGs, MDPs, MOVs, AOVs, etc.
  - Circuit breakers for pump/valve motors
  - Need to be consistent with how data was collected
    - That is, should individual piece parts be modeled explicitly or implicitly
    - For example, actuation circuits (FTS) or room cooling (FTR)

Active Components Require "Support"

- Signal needed to "actuate" component
  - Safety Injection Signal starts pump or opens valve
- Support systems might be required for component to function
  - AC and/or DC power
  - Service water or component water cooling
  - Room cooling

Support System Dependencies

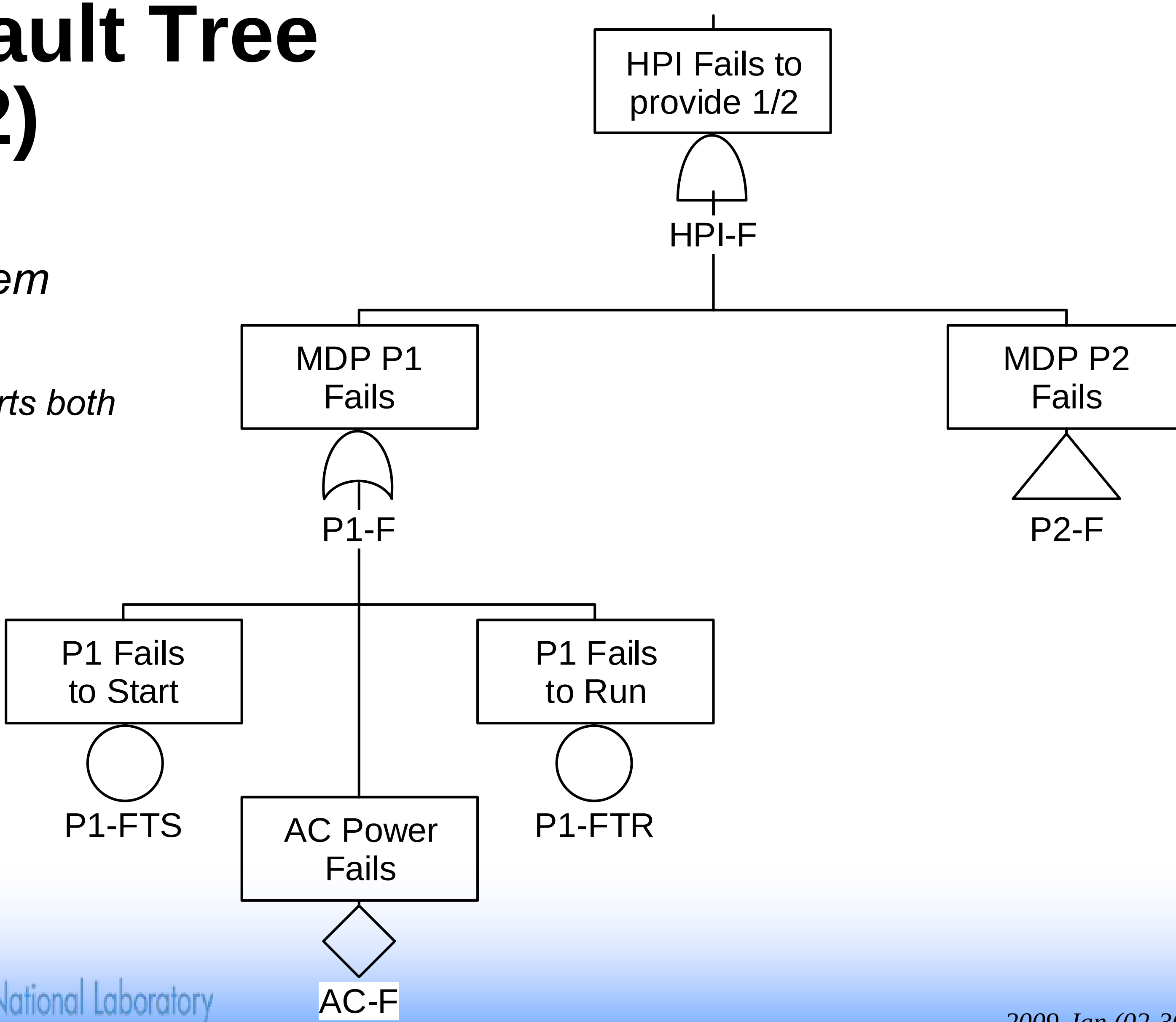
- Can be modeled at system level, train level or component level
- Dependency matrix is frequently used to document identified dependencies

Note: If support system serves more than one component or system, it is modeled separately (see next two slides)

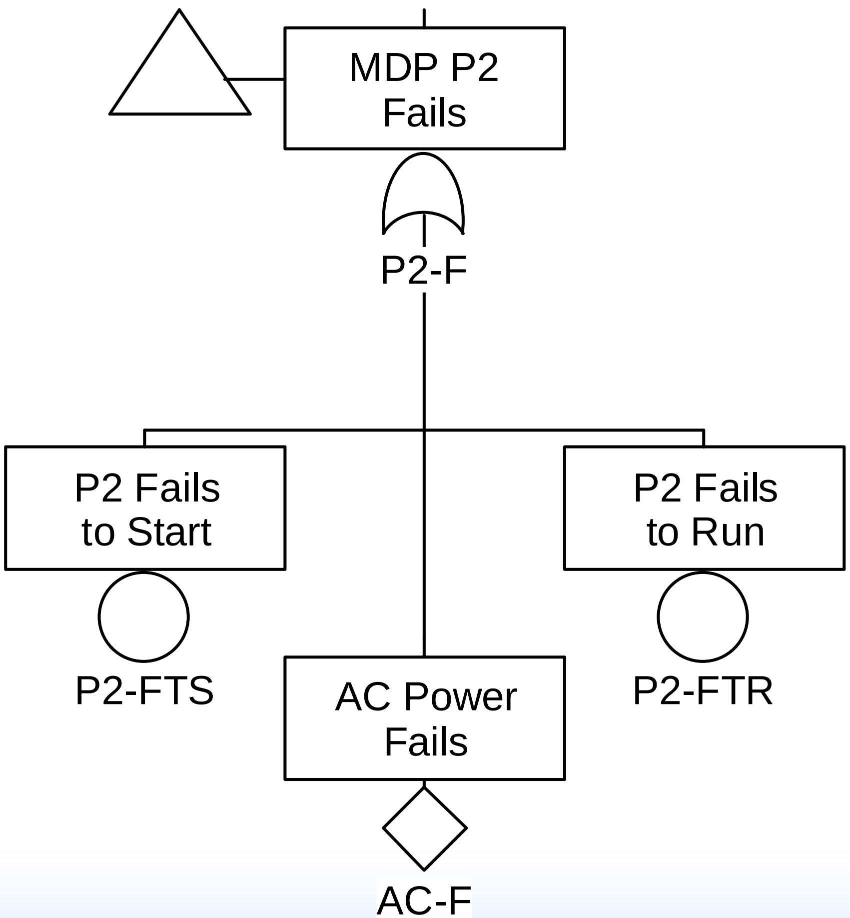
HPI Fault Tree (1 of 2)

Support System Dependency

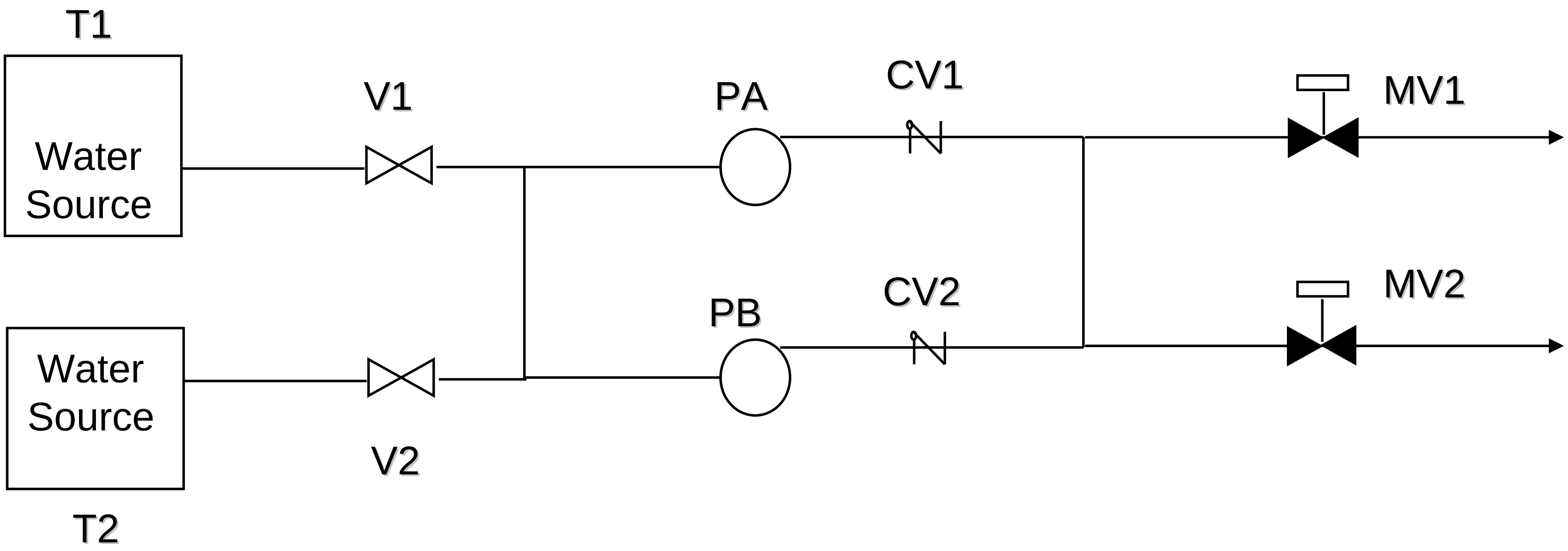
AC power supports both pumps 1 and 2



HPI Fault Tree (2 of 2)



Practice Example



Success Criteria: One pump flow through both MV's

System Modeling Techniques for PRA

Lecture 3 - System Models

January 2009 – Bethesda, MD

Idaho National Laboratory

INL

Objective

- **Develop understanding of System Modeling, including:**
  - **Modeling goals**
  - **Modeling techniques and variations**

Outline

- System Modeling Approach
- Missions
- Success Criteria
- Boundary Conditions
- Parallel/Series System Modeling
- System Level Fault Tree Modeling
- Results

System Modeling Approach

- Focus on individual plant systems
- Issues addressed by logic model
  - How can the system fail?
  - How likely is failure?
  - What are the dominant contributors?
- Key questions for understanding the system
  - What does the system do?
  - What is “failure”?
  - What is the “system”? What are the analysis boundaries?

System Mission Affects Model

- Demand based missions (binomial)
  - Normally in standby
  - Required to perform one (or more) times
  - e.g., actuation systems, relief valves
- Time based missions (Poisson)
  - Either in standby or normally operating
  - Required to operate for some length of time, which affects unreliability
  - e.g., ECCS, SWS

Success Criteria

- Needed to employ binary logic modeling
  - Note that same system may be modeled under different conditions for different initiators
- Developed from physical analyses
- Can be sequence-dependent
- Must consider details of expected mission (e.g., mission time, actuation signals, status of support systems)

Analysis Scope and Boundaries

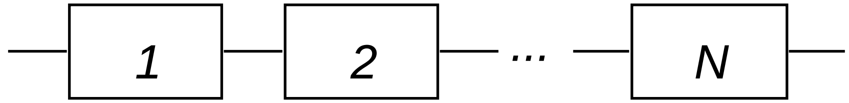
- Plant Operating Mode
- Hardware
  - power supply/powered system
  - common actuation/actuated system
  - cooling system/cooled system
  - cross-ties
- Failure Modes
  - internal vs. "external"
  - errors of commission
- Mission Time
- Organization

Definition of Problem Must be Specific and Precise

- Sample Success Criteria
  - Improper:
    - HPIS is successful
  - Proper:
    - Uninterrupted flow from 2/3 HPIS pumps for 24 hours
    - Generally defined from thermal-hydraulics calculations

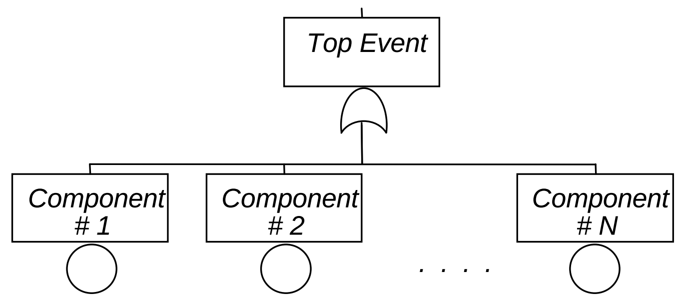
Series System

Schematic



(P&ID)

Fault Tree



(OR Gate)

Boolean and Quantification

$$Top = \sum_{i=1}^{N} X_i$$

(Cut Sets)

$$P\{Top\} = 1 - \prod_{i=1}^{N} (1 - Q_i) \quad \textit{(if independent)}$$

$$\approx \sum_{i=1}^{N} Q_I \quad \textit{(rare event approximation)}$$

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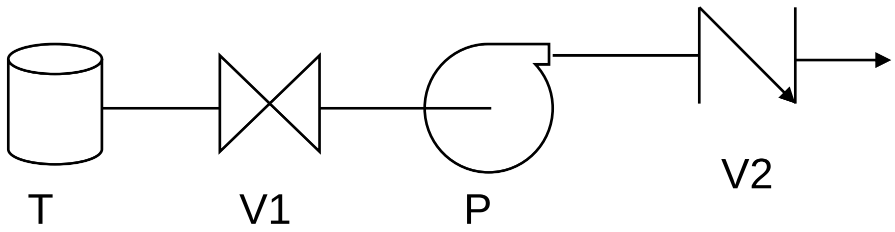
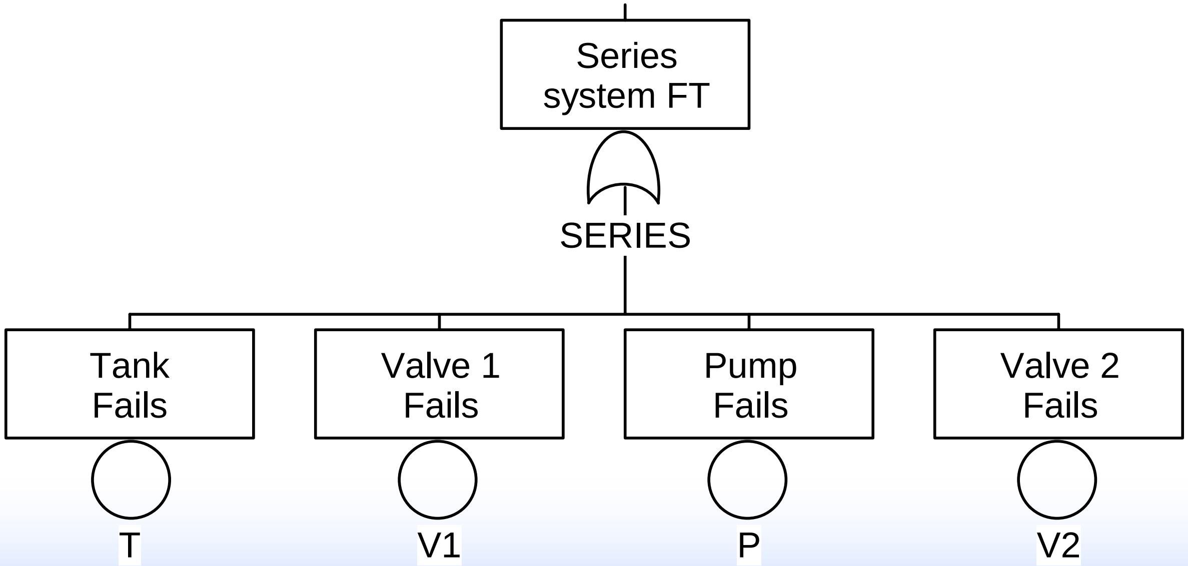
Series System Example

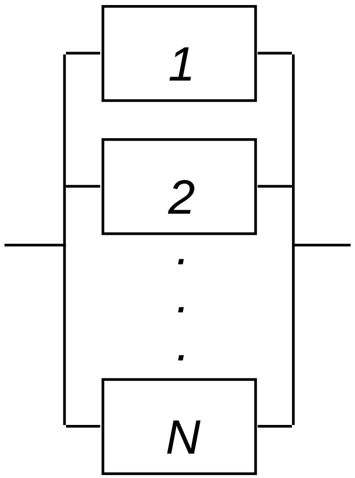


- **Any component failure fails the system**



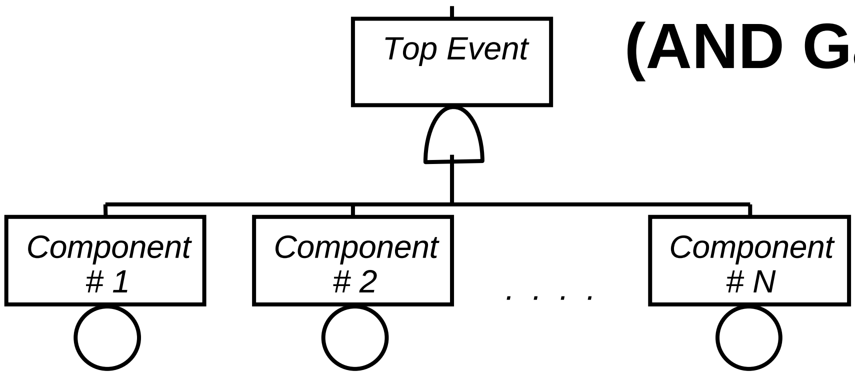
Parallel System

Schematic



(P&ID)

Fault Tree



(AND Gate)

Boolean and Quantification

$$Top = \prod_{i=1}^{N} X_i$$

(Cut Sets)

$$P\{Top\} = \prod_{i=1}^{N} Q_i \quad \text{(if independent)}$$

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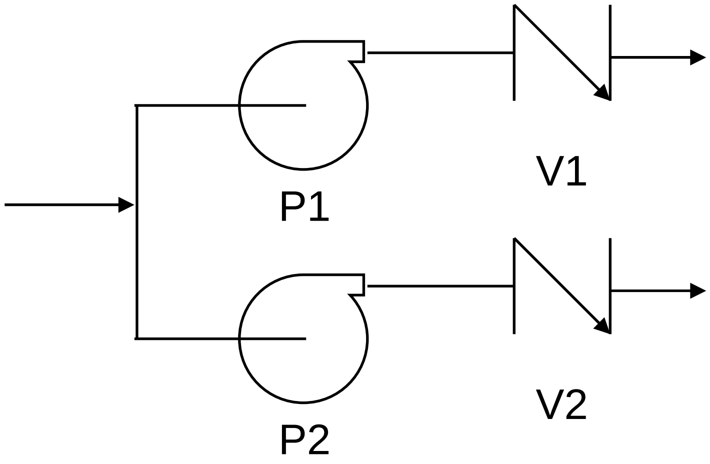
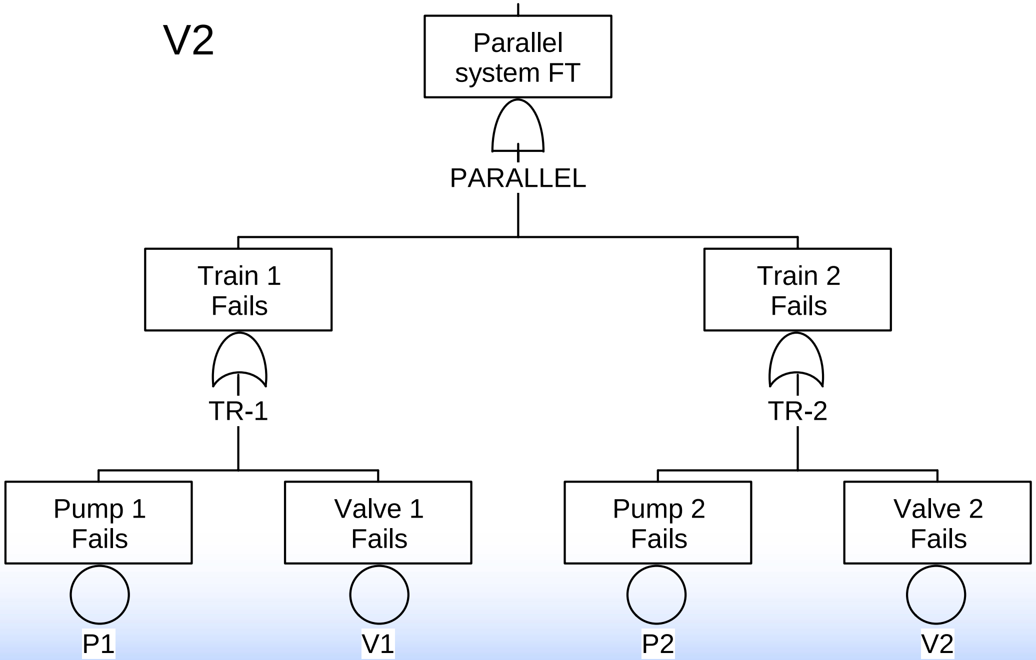
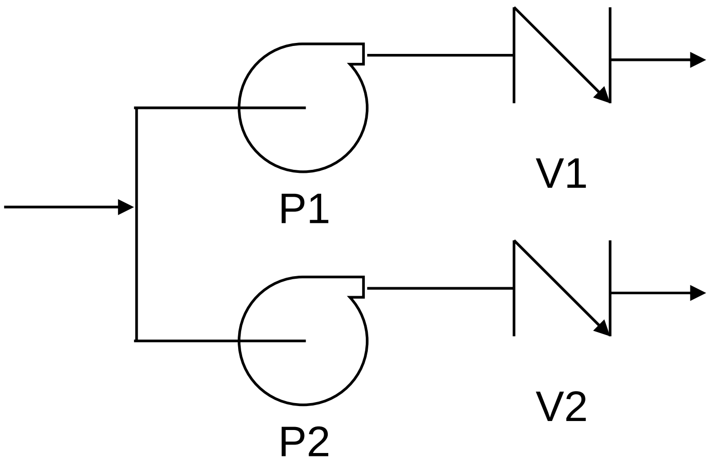
Parallel System Example



System redundancy requires multiple component failures to fail system

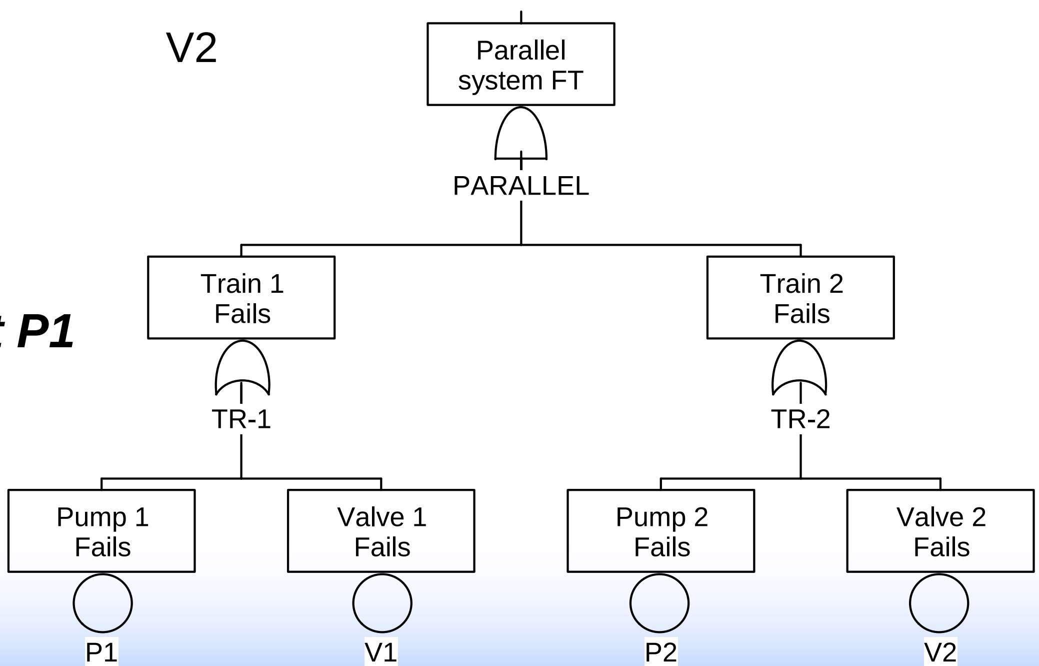


Parallel System Example



System redundancy requires multiple component failures to fail system

Set basic event P1 to TRUE



Fault Tree Construction

- Items to consider
  - Dependent Failures
  - Functional Dependencies
    - Support Systems
  - Shared Equipment Dependencies
    - LPR requires same pumps as LPI
  - Test/Maintenance Dependencies
    - Single T&M procedure can make multiple components unavailable
  - Common Cause Failures

Fault Tree Construction (cont.)

- **Human errors in fault trees**
  - **HEs lead to additional basic-events/failure-modes**
  - **Examples: Fail to restore, failure to initiate, improper termination (rarely modeled)**
  - **HEs in fault trees are local in scope**
- **Modeling T&M unavailability can result in illogical cut sets**
  - **Multiple redundant trains are generally not out at same time**
  - **Using complemented events (e.g., A_{tm} * /B_{tm}) complicates the quantification**
- **Putting recovery in FT might give overly optimistic results**

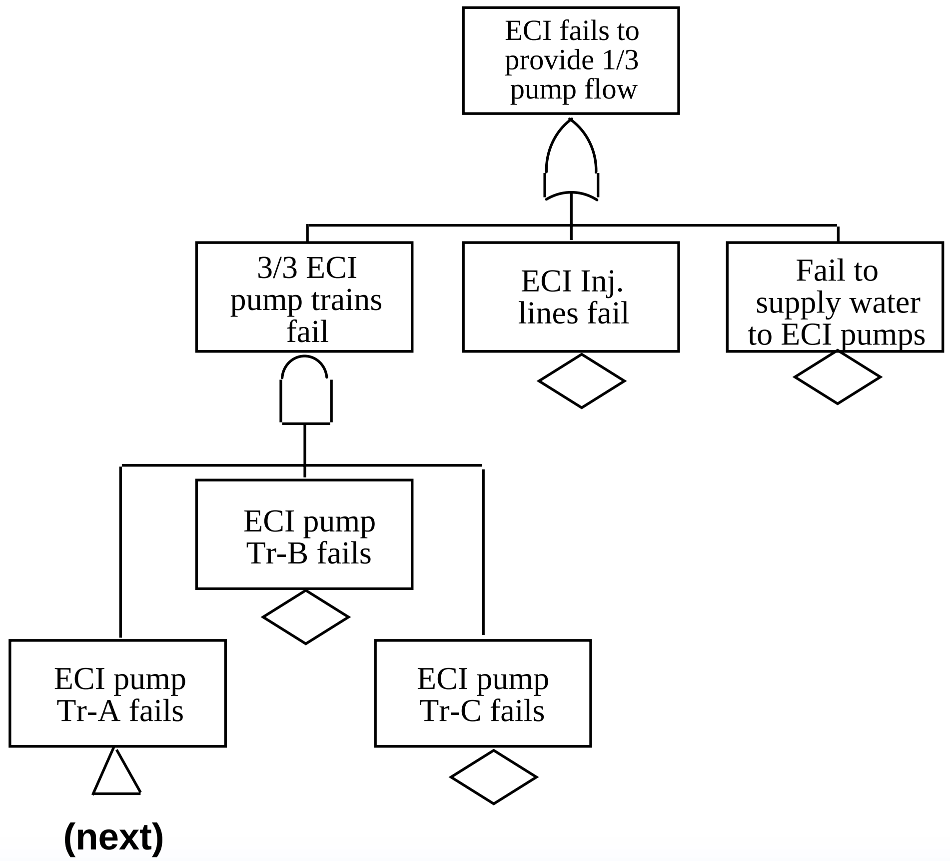
Fault Tree Pitfalls

- Inconsistent or unclear basic event names
  - X*X = X, so if X is called X1 in one place and X2 in another place, incorrect results are obtained
- Missing dependencies or failure mechanisms
  - An issue of completeness
- Unrealistic assumptions
  - Availability of redundant equipment
  - Credit for multiple independent operator actions
  - Violation of plant LCO
- Logic loops
  - Will talk about what they are and how to fix them…

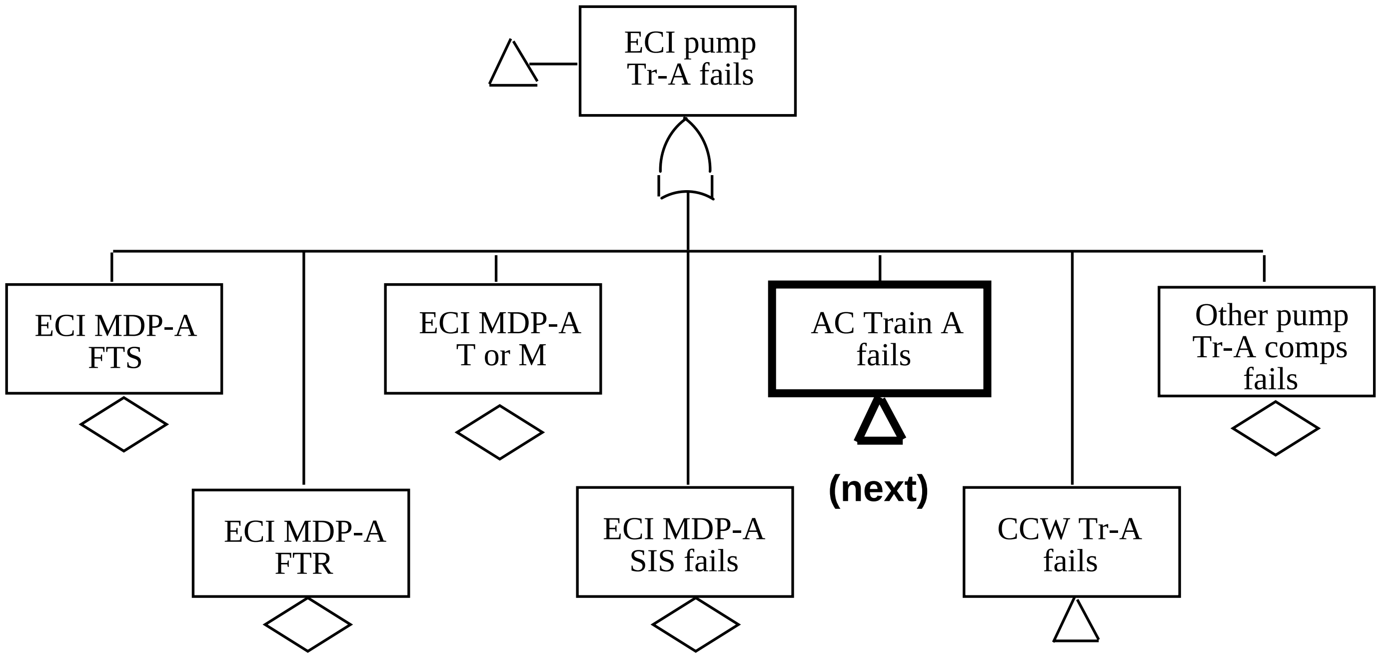
Logic Loops Result From Circular Support Function Dependencies

- ECI pump requires AC power
- AC power supplied from either Offsite Power or Diesel Generators (DGs)
- DGs require Component Cooling Water (CCW) for cooling
- CCW pumps require AC power

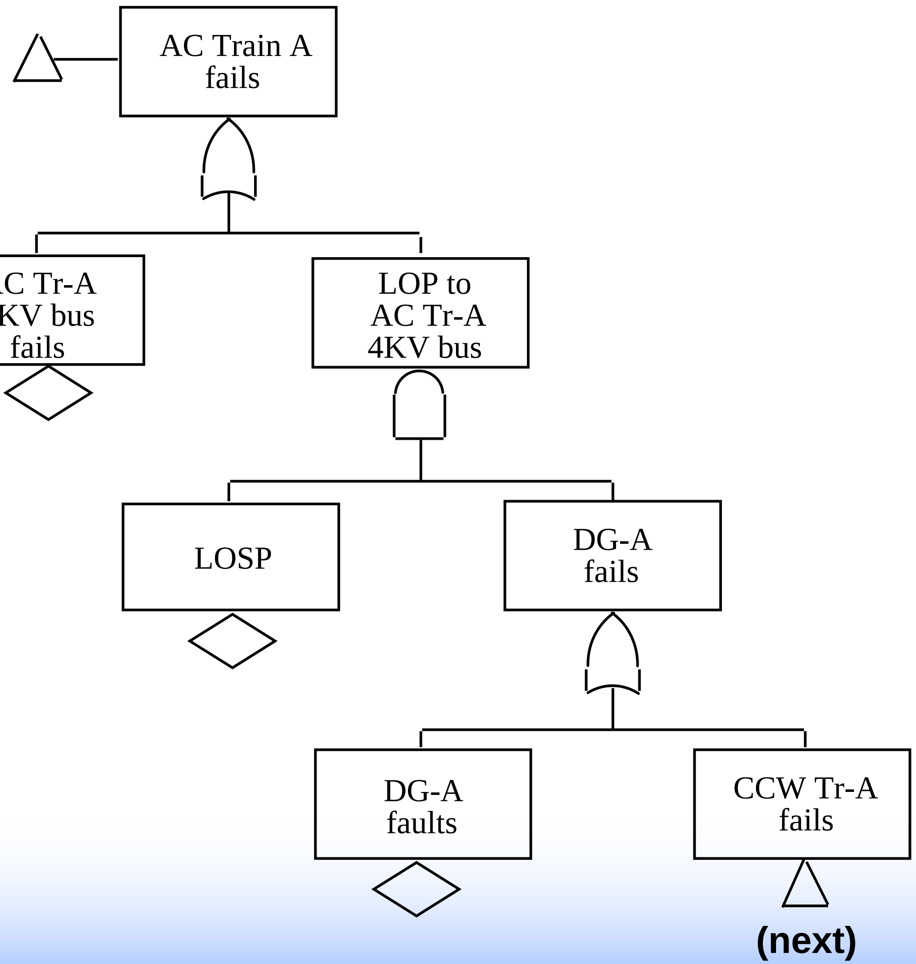
Logic Loops 1



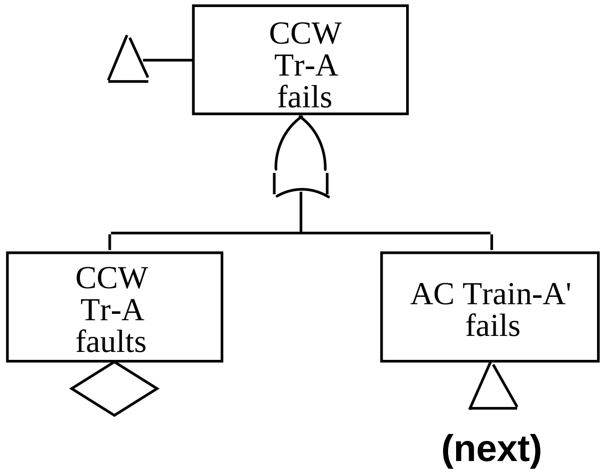
Logic Loops 2



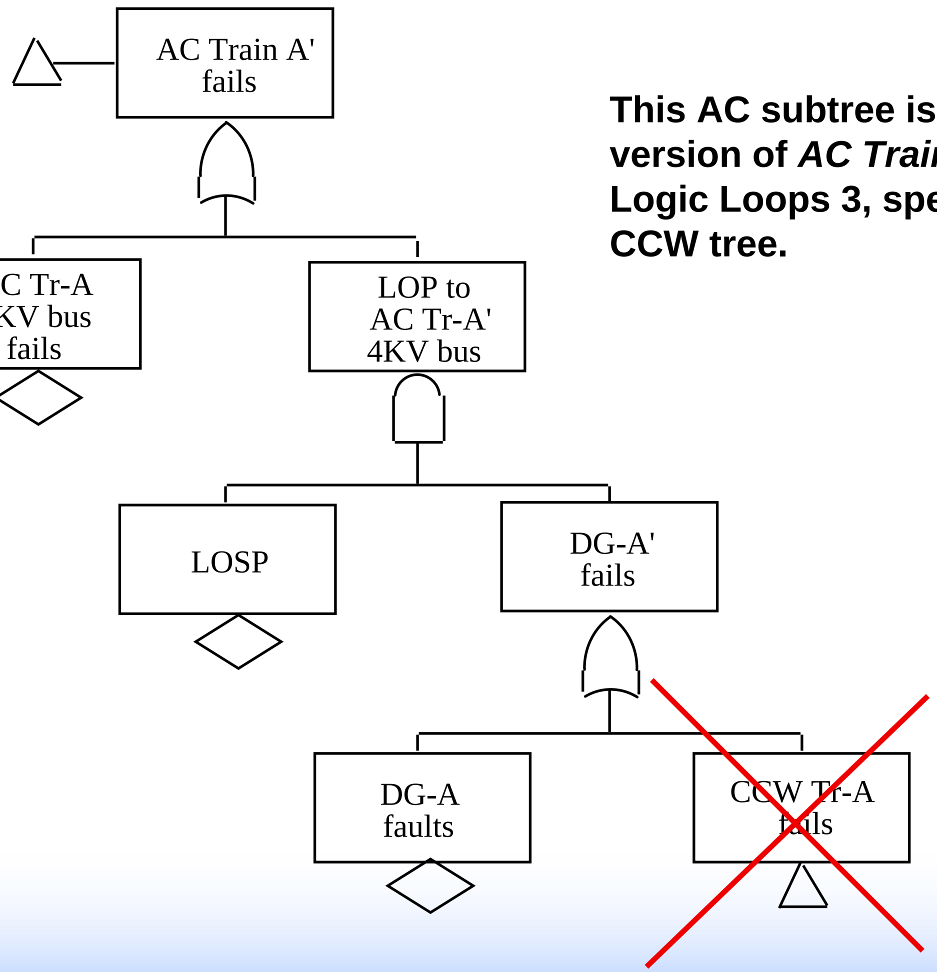
Logic Loops 3



Logic Loops 4

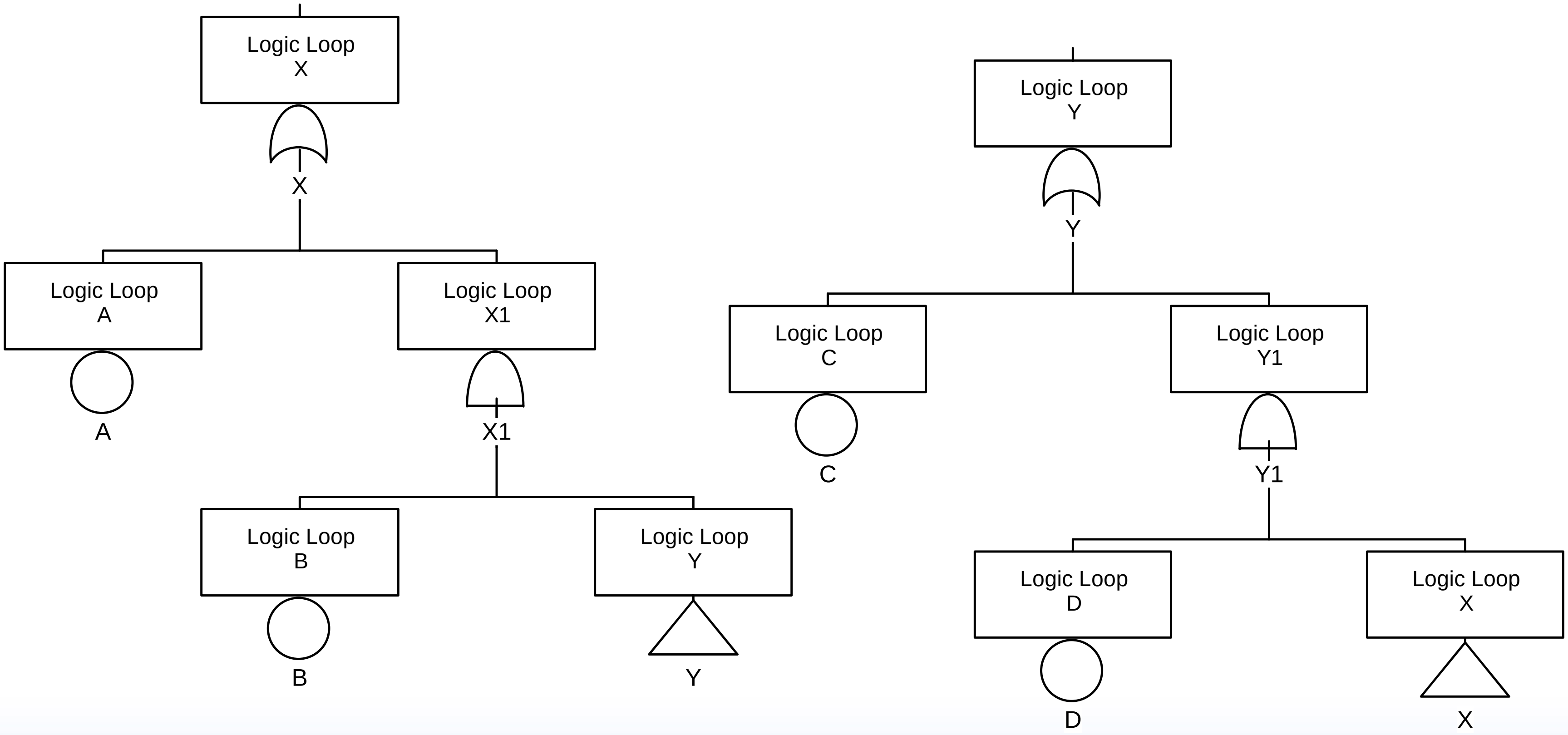


Logic Loops 5



This AC subtree is a new version of *AC Train A fails* (from Logic Loops 3, specific for the CCW tree.

Generate Cut Sets



Results

- Sanity checks on cut sets
  - Symmetry
    - If Train-A failures appear, do Train-B failures also appear?
  - Completeness
    - Are all redundant trains/systems really failed?
    - Are failure modes accounted for at component level?
  - Realism
    - Do cut sets make sense (i.e., Train-A out for T&M ANDed with Train-B out for T&M)?
  - Predictive Capability
    - If system model predicts total system failure once in 100 system demands, is plant operating experience consistent with this?

What is Wrong?

System XYZ Pumps Fail =

PumpA-FTS * PumpB-FTS +

PumpA-FTS * PumpB-FTR +

PumpA-FTS * PumpB-TM +

PumpA-FTR * PumpB-FTR +

PumpA-FTR * PumpB-TM +

PumpA-TM * PumpB-FTS +

PumpA-TM * PumpB-FTR +

PumpA-TM * PumpB-TM.

PRA Modeling Mindset

- All **systems** can **fail**
  - **Under what conditions is failure more likely? How likely are these?**
  - **Are all potentially significant mechanisms identified and treated?**
- **Catastrophic system failures are rare events**
  - **May need creative search for failure mechanisms**
  - **Maximize use of available information, which implies that Bayesian methods to be used**
- **System failure is a "systems" issue**
  - **Need to identify and address systems interactions**
  - **Avoid drawing analysis boundaries too tightly**

System Modeling Techniques for PRA

Lecture 4 – Uncertainty

January 2009 – Bethesda, MD

Idaho National Laboratory

Objective

- Understand implications of uncertainty associated with PRAs
- Understand different types and sources of uncertainty
- Understand mechanics of how uncertainty is calculated
- Understand why we calculate uncertainty

- Outline
  – Types of uncertainties
  – Uncertainty Measures
  – Propagation of Uncertainties

Stochastic Uncertainties

- **Measure of randomness or variability in process**
  - **e.g., coin flip - sometimes heads, sometimes tails**
- **Also called random or *aleatory* uncertainty**
- **Distribution is result of assumptions about a process**
  - **Failure occur randomly in time (Poisson)**
  - **Failure occur randomly given a demand (binomial)**
- **Distribution is a function of parameter values (e.g., failure rate λ), which are uncertain**

State-of-Knowledge Uncertainties

- **Lack of accuracy in model parameters (i.e., uncertainty in λ's)**
- **Also called subjective or *epistemic* uncertainty**
- **Distribution reflects data, relevant model predictions, engineering judgment**
- **Typically generated using Bayesian methods (covered in Statistics course)**

Uncertainties

- **Summary Measures**
  - **Mean:** $E[\lambda] = \int_0^{\infty} \lambda \ \pi(\lambda)\ d\lambda$ Note: $\int_0^{\infty} \pi(\lambda) d\lambda = 1$
  - **Variance:** $E[(\lambda - E[\lambda])^2] = \int_0^{\infty} (\lambda - E[\lambda])^2 \pi(\lambda)\ d\lambda$

    $= E[\lambda^2] - (E[\lambda])^2$
  - **αth percentile:** $\alpha = P\{\lambda \leq \lambda_\alpha\} = \int_0^{\lambda_\alpha} \pi(\lambda)\ d\lambda$
  - **95th percentile:** $0.95 = \int_0^{\lambda_{0.95}} \pi(\lambda)\ d\lambda$

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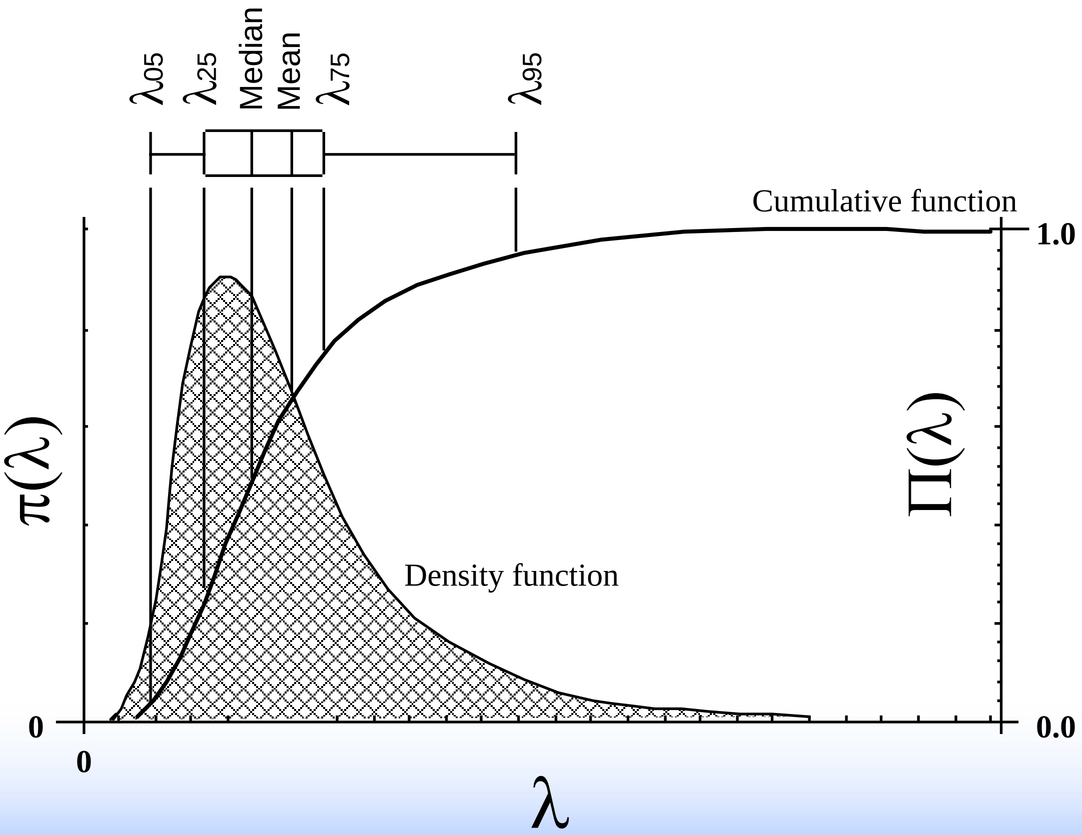
Uncertainties

- **Probability of Parameter Value**



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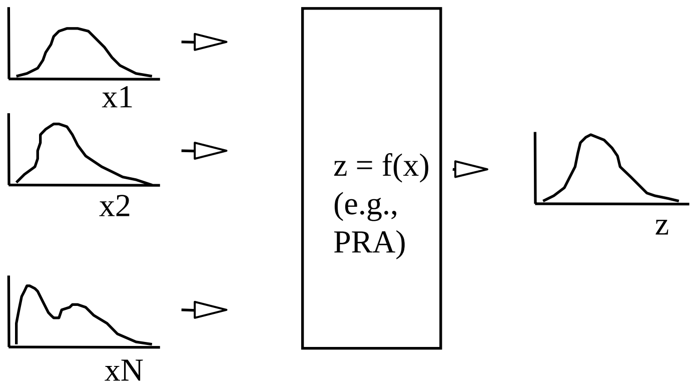
Error Factors

- **Valid for lognormal distributions**
- **EF =** $\sqrt{\lambda_{95} / \lambda_{05}}$
- **PRA typically assume lognormal distributions and 90% coverage.**
- **Also, for lognormal**
  - **EF = median /** λ_{05}
  - **EF =** λ_{95} **/ median (typically used)**

Propagation of Uncertainties

- **Problem**



Remember, a PRA is basically a very large boolean algebra equation (or function)

Propagation of Uncertainties

- **Method of Moments**
  - **Let X and Y be independent variables, and let**

    $Z = X + Y$
  - **The mean and variance of Z can then be found:**

    $E[Z] = E[X] + E[Y]$

    $Var[Z] = Var[X] + Var[Y]$ (if X and Y independent)

Propagation of Uncertainties

- **Method of Moments**
  - More generally, if X and Y are dependent,

$$
\begin{aligned}
Var[Z] &= Var[X+Y] \\
&= E[(X+Y-E[X+Y])^2] \\
&= E[(X+Y)^2] - E[X+Y]^2 \\
&= E[X^2] + 2E[XY] + E[Y^2] - E[X]^2 - 2E[X]E[Y] - E[X]^2 \\
&= Var[X] + Var[Y] + 2Cov[X,Y]
\end{aligned}
$$

Propagation of Uncertainties

- **Method of Moments**
  - **Let X and Y be independent variables, and let**

    $Z = X \bullet Y$
  - **Then**

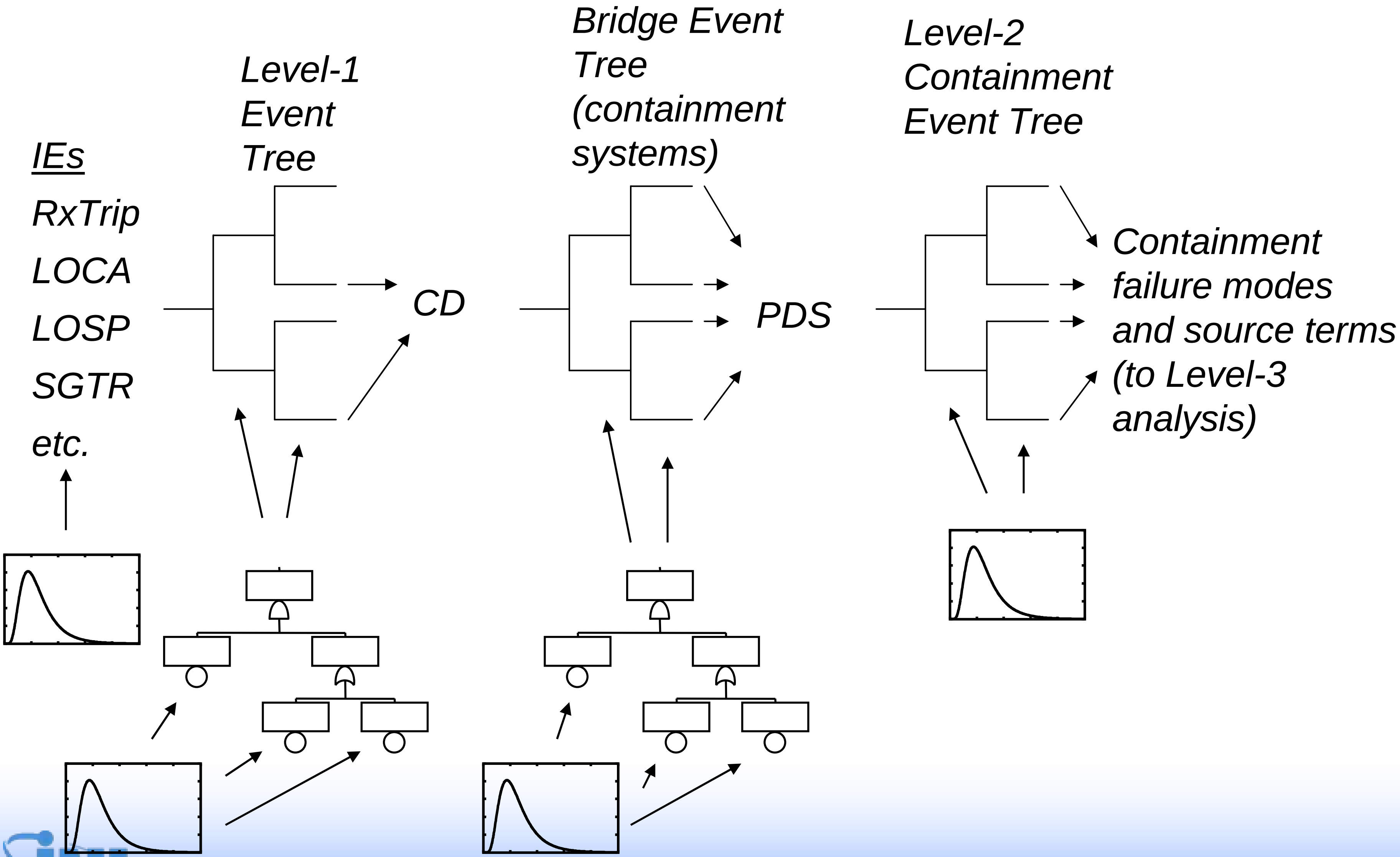
    $E[Z] = E[X] \bullet E[Y]$

    $Var[Z] = Var[X] \bullet Var[Y] + Var[X]E[Y]^2 + Var[Y]E[X]^2$

Analytical Methods Impractical

- Typical PRA comprises
  - Hundreds (if not thousands) of basic events
  - Many tens of significant core damage sequences
  - Often hundreds of thousands (if not millions) of core damage sequence cut sets
- Analytical methods - not just difficult, but infeasible

The Problem: Level-1/2 PRA Uncertainty Integration

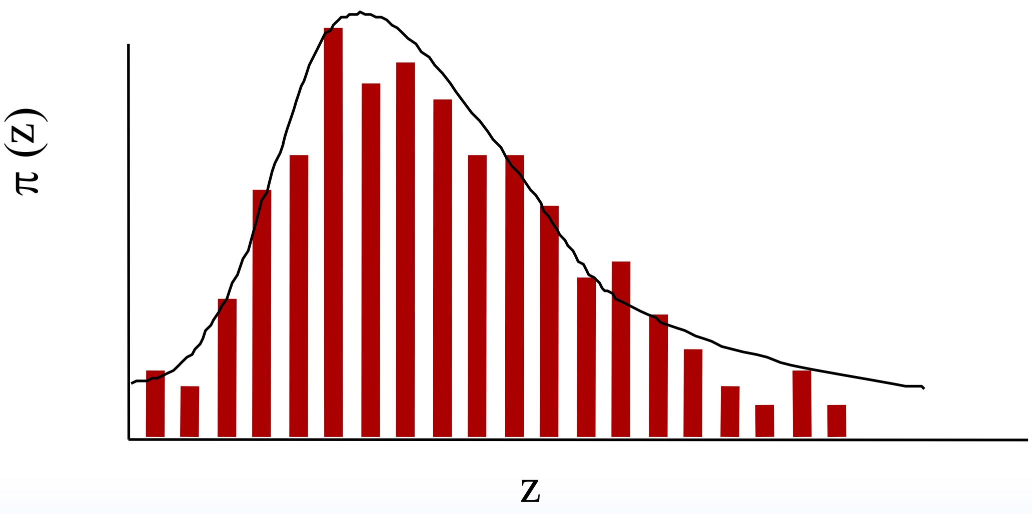


Propagating Uncertainties

- Simulation methods are only practical approach
  - Simply sample from possible input values many times and plot results
- Two simulation methods commonly used
  - Monte Carlo
  - Latin Hypercube

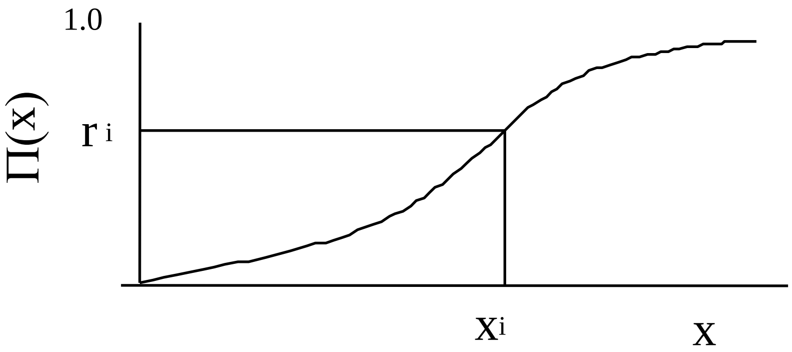
Propagation of Uncertainties

- **Monte Carlo**
  - **Empirically generates distribution for Z = f(X, Y) by sampling from distributions for X and Y**



Propagation of Uncertainties

- **Monte Carlo**
  - **Sampling approach (one variable)**



  - **Cautions**
    - **Sampling extreme values**
    - **Accuracy (proportional to 1/$\sqrt{N}$) (N=# samples)**
    - **Sampling algorithm and random # generator**

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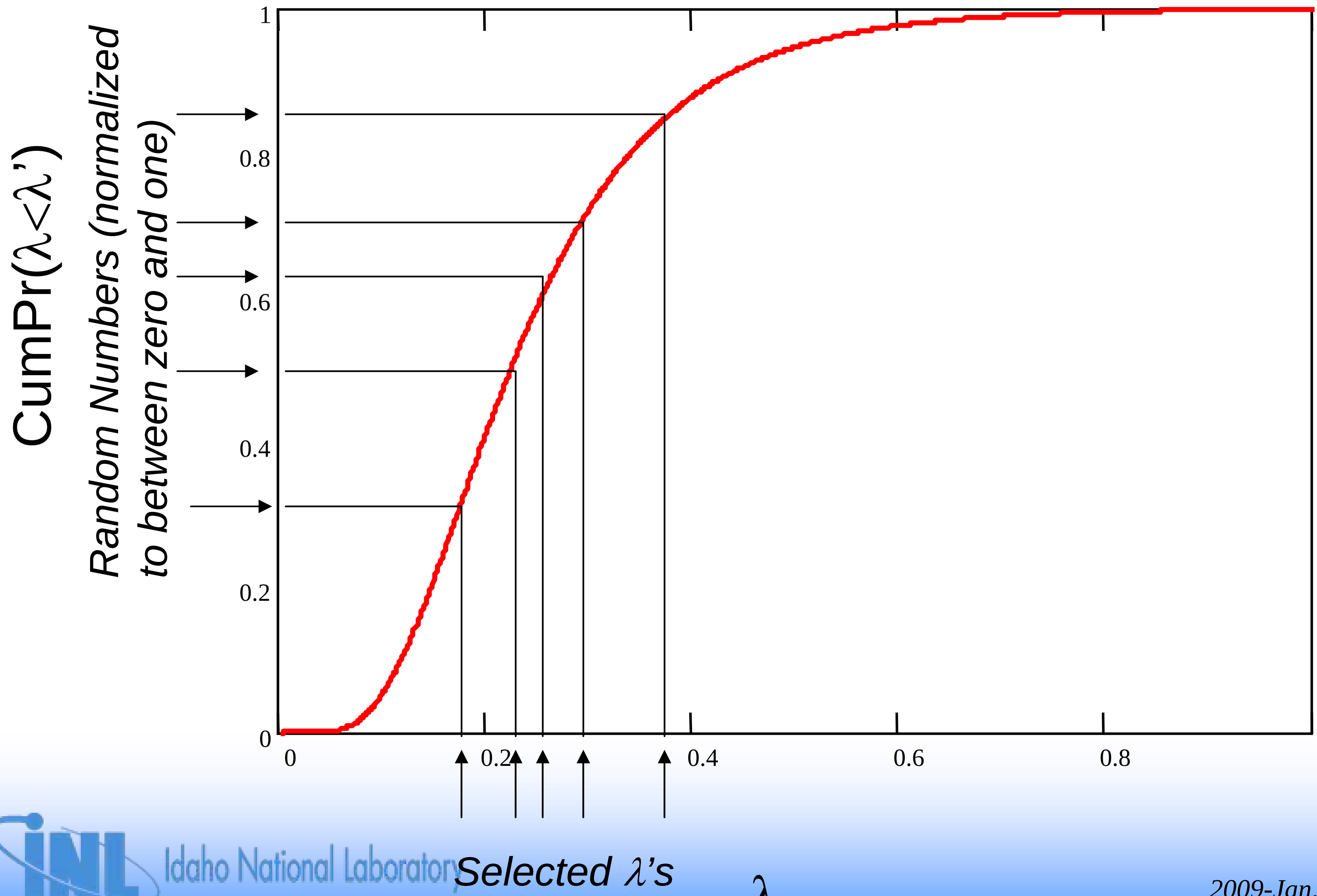
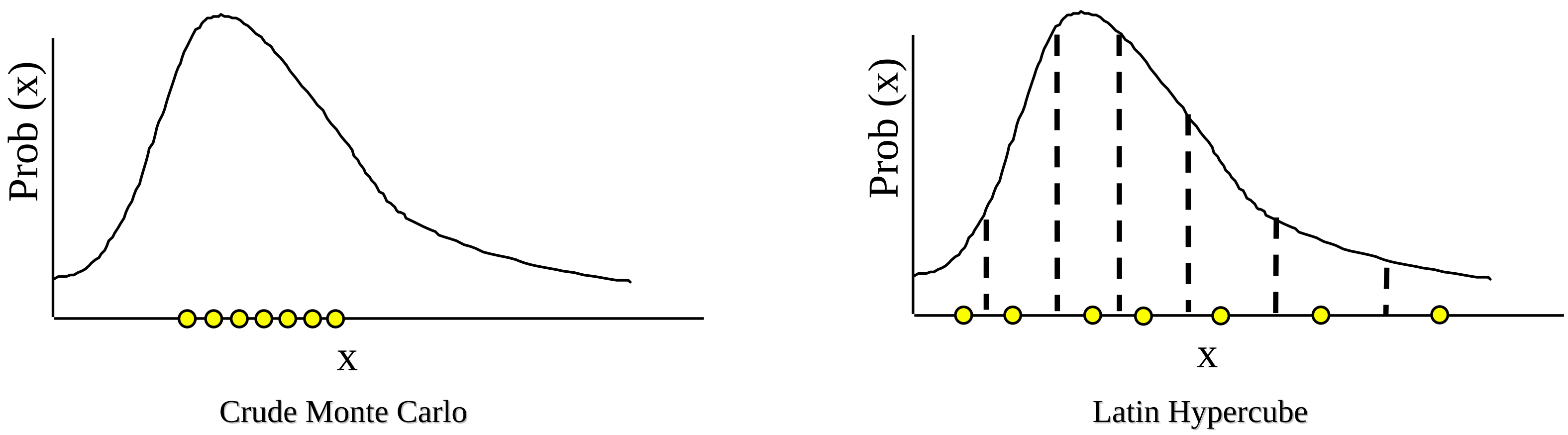
Monte Carlo Sampling (5 Samples) on input parameter λ



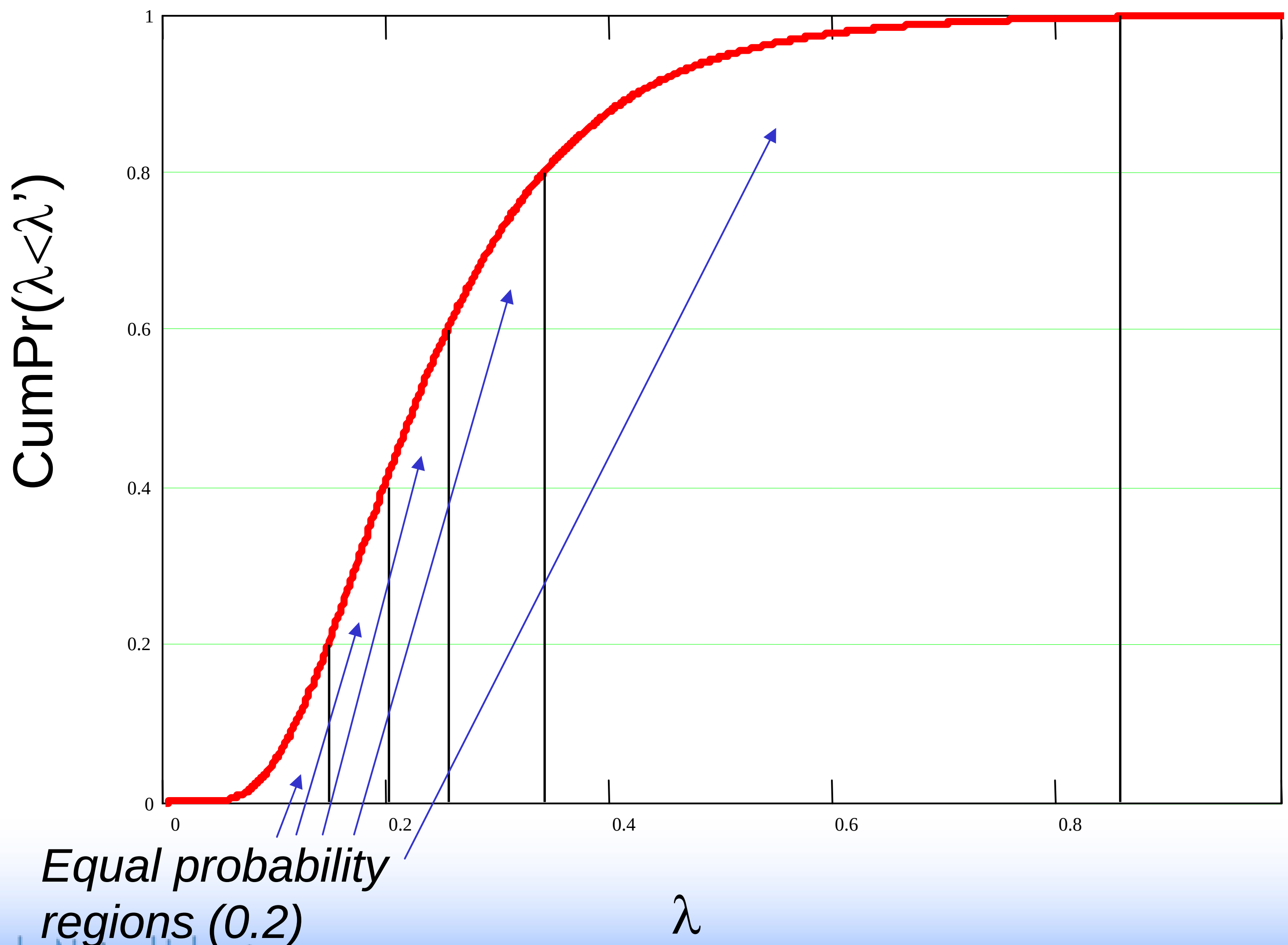
Propagation of Uncertainties

- **Latin Hypercube**
  - **Empirically generates distribution for Z = f(X) by stratified sampling from distribution for X**



  - **Better coverage of extreme values than crude Monte Carlo**

Latin Hypercube Sampling (one λ selected from each equal-probability area)



System Modeling Techniques for PRA

Lecture 5 - Event Trees

January 2009 – Bethesda, MD

Idaho National Laboratory

Objectives

- Understand underlying process implied by event tree models
- Understand common event tree conventions
- Understand model applications and limitations

- Outline
  - Appropriate applications for event trees
  - Event tree conventions and construction
  - Modeling of dependencies

Event Trees

- Model what happens after initiating event
  - Typically (but not necessarily), a chronological ordering of major events
- Reflect system interactions
- Provide vehicle for sequence quantification
  - A sequence is an initiating event combined with a set of top events, usually system successes and failures
- Provide simple display of results

Event Tree Underlying Model

- After initiating event, safety barriers are challenged
- Barrier (system) failure is an aleatory event
  – IE * barrier success/failure → assumed to be Poisson distributed
- Overall sequence frequency is $\lambda \phi$

  (frequency of IE) x (Probability of system failure)
- λ and ϕ have uncertainty (epistemic)

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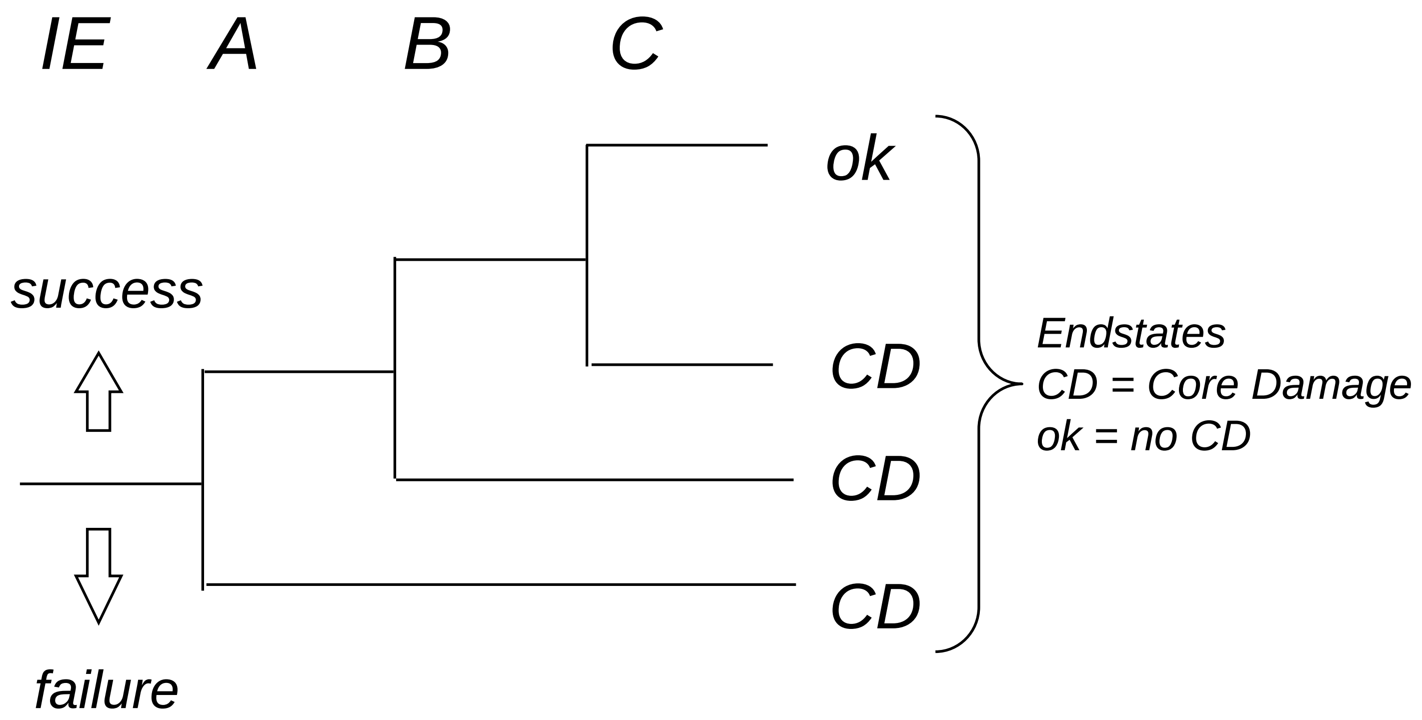
Event Tree Models Sequence of Events



That is, IE occurs, then plant systems A, B and C are challenged.

Two Basic Approaches for Event Tree Models

- Analysis process includes two methods
- Event trees with boundary conditions (many event trees constructed, each with a unique set of support system BC)
  - Involves analyst quantification and identification of intersystem dependencies
  - Sometimes called Large-ET/Small-FT or PL&G approach
- Linked fault trees (event trees are the mechanism for linking the fault trees)
  - Employs Boolean logic and fault tree models to pick up intersystem dependencies
  - Sometimes called Small-ET/Large-FT approach, used by most of the PRA community

Event Tree Construction

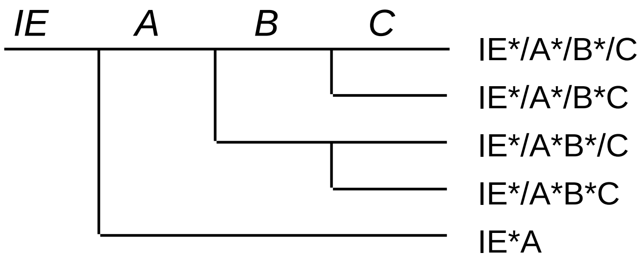
- Modeling Approach
  - Linked fault trees
    - Automatic treatment of shared event dependencies
    - One-step quantification
    - Often use large, general-purpose fault trees
    - Used by SPAR models and majority of utility PRAs

Event Tree with Boundary Conditions

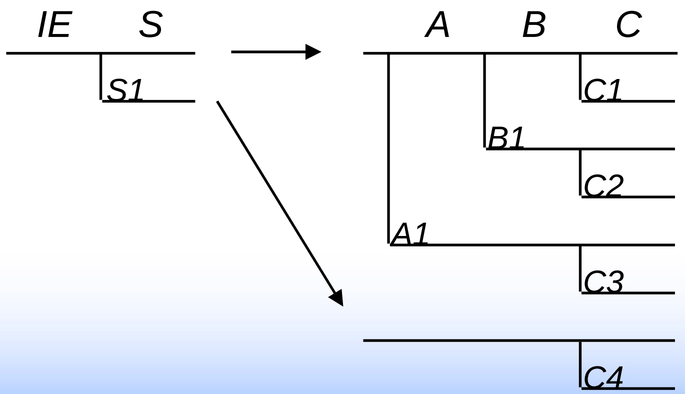
- **Modeling Approach**
  - **Objective: Explicitly separate-out dependencies to facilitate quantification of sequences**
  - **Focuses attention on context (i.e., the boundary conditions) for performance**
  - **Requires intermediate numerical results (conditional split fractions)**
  - **Often implemented using multiple, linked event trees**
  - **Sometimes referred to as Large-ET approach**

Both Event Tree Approaches Link Models*

Fault trees to event trees:



Event trees to event trees:



** Necessary in order to accurately reflect dependencies*

Dependent Failures Overview

- **Importance of Modeling**
  - **For systems with defense in depth, an accident requires failure of multiple safety barriers**
  - **Multiple independent failures are highly unlikely (unless safety barriers are unreliable)**
  - **Scenarios involving *coupled* failures of barriers will dominate risk**
  - **If A and B are dependent, then**

$$P(AB) \neq P(A) * P(B), \text{ and instead…}$$

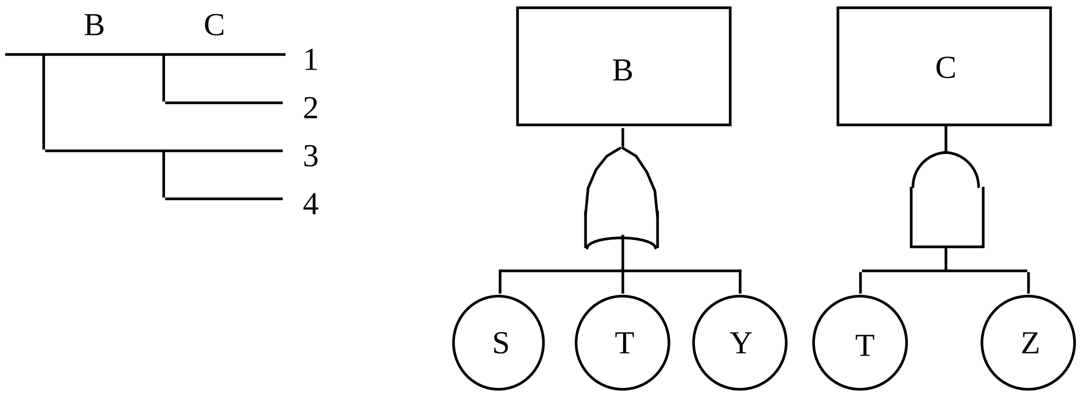
$$P(AB) = P(A) * P(B|A) = P(B) * P(A|B)$$

Modeling Dependent Failures

- **Analysis Approaches**
  - **Explicit modeling**
  - **Implicit modeling**
    - **Parametric common cause failure analysis, discussed later**

Dependencies Modeled in Fault Trees

- **Example of shared equipment dependency:**



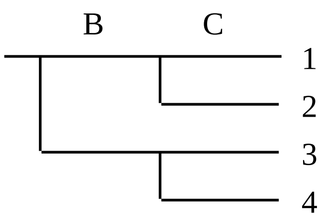
- **Sequence 4 = B * C (i.e., both B and C occur/fail)**

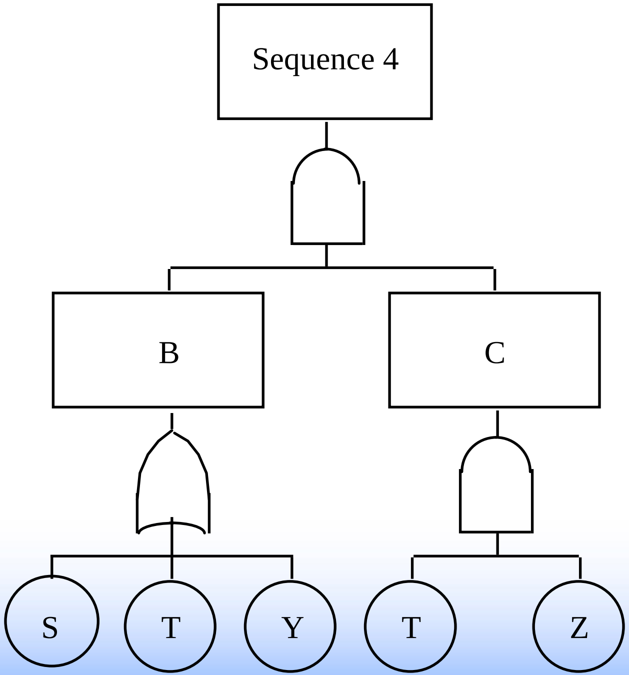
Shared Equipment Dependencies

- **Fault Tree Linking for Sequence 4 (B and C)**
  - **Sequence 4 = (S + T + Y)*(T*Z)**

= (S*T*Z + T*T*Z + Y*T*Z)

= T*Z



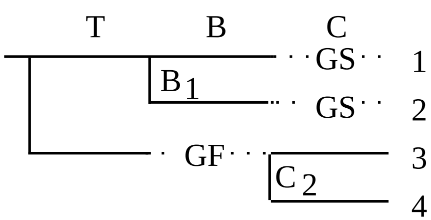


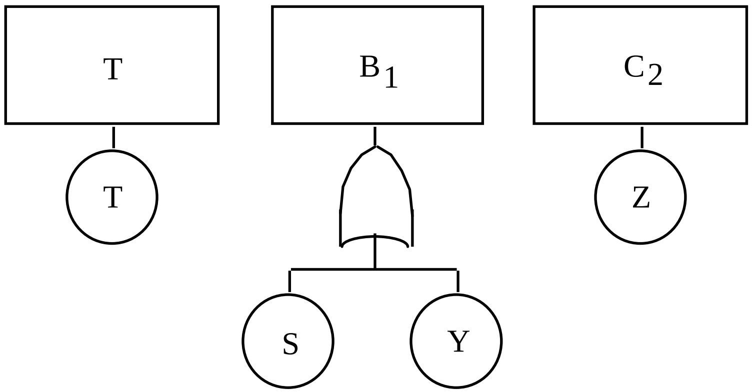
Practice Example

- **Re-Solve Sequence 4 with System-B as an AND gate, and System-C as an OR gate.**

Dependencies Modeled in Event Trees

- **Event Trees with Boundary Conditions**
  - **Dependency can be represented with a separate top event (usually used for support systems)**





$$\phi_{B_1} = \Pr\{B \,|\, /T\} \approx \phi_S + \phi_Y$$

$$\phi_{C_2} = \Pr\{C \,|\, T,B\} = \phi_Z$$

GS - Guaranteed Success

GF - Guaranteed Failure

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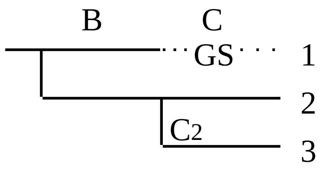
Shared Equipment Dependencies

- **Event Trees with Boundary Conditions**
  - **Conditional split fractions can also be used to model shared equipment dependencies**
  - **Example:**

Sequence 3 = B*C = (S + T + Y)*(T*Z) = T*Z

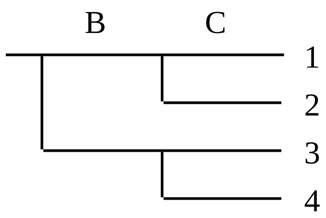


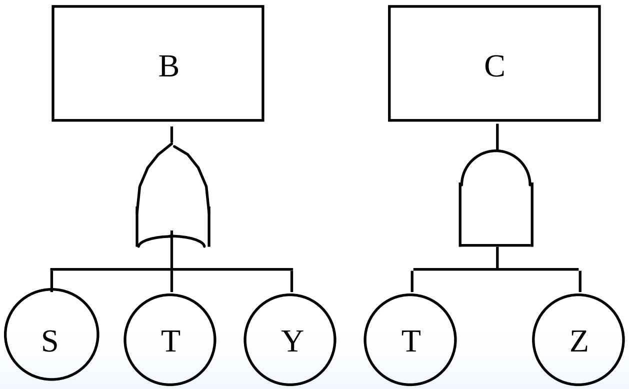
$$\phi_{C_2} = \Pr\{C \mid B\} = \frac{\Pr\{B \text{ AND } C\}}{\Pr\{B\}} = \frac{\Pr\{T * Z\}}{\Pr\{S + T + Y\}}$$

$$\approx \frac{\phi_T \cdot \phi_Z}{\phi_S + \phi_T + \phi_Y}$$

Practice Example

- **Shared equipment dependency in linked fault trees**
- **Solve for Sequence 2 (via fault tree linking, need to use Boolean Algebra rules from Lecture-3 on Fault Trees)**





System Modeling Techniques for PRA

Lecture 6 - Sequence Models

January 2009 – Bethesda, MD

Idaho National Laboratory

INL

Objectives

- Understand general process of modeling "systems"
- Greater understanding of event tree modeling techniques

- Outline
  - PRA Modeling Process
  - Initiating Events
  - Event Tree Modeling Techniques
    - Functional Event Trees
    - Systemic Event Trees
    - Sequence Logic and Cut Sets

PRA Modeling Process

- Identify initiating events
- Identify mitigating functions
- Develop event trees for sequence logic
- Develop success criteria for top events
- Develop fault trees for top events
- Develop detailed sequence logic
  - Sequence cut sets (linked fault tree approach)
  - Conditional split fractions (Event Trees w/BC)

Initiating Events

- Methods for Identification
  - Deductive methods
    - Master logic diagram (what causes a reactor trip?)
  - Failure modes and effects analysis (FMEA)
  - Analysis of historical events
    - Licensee event reports
  - Comparison with other studies
  - Feedback from modeling
    - Support system dependencies identified

Initiating Events

- Potential Problem Areas
  - Quantification given little or no statistical evidence
    - Large LOCA frequency (none have occurred)
  - Violations of Poisson assumptions
    - Time dependent failure rate (aging)
  - Too many initiating events
  - Lack of completeness
  - Ambiguity in definition
    - Does loss of feedwater imply the condensate system is unavailable?

Development of Event Trees

- **Unique event tree developed for each initiating event**
  - **Can group like initiators if they have similar impacts to the plant**
- **Based on safety functions necessary to achieve safe shutdown (functional event tree)**
- **Top events list systems capable of performing necessary safety functions (success criteria)**

Functional Event Tree

High-level representation of vital safety functions required to mitigate abnormal event

- Generic response of the plant to achieve safe and stable condition

- What safety functions must be fulfilled?
  - For example:

    Reactor subcritical

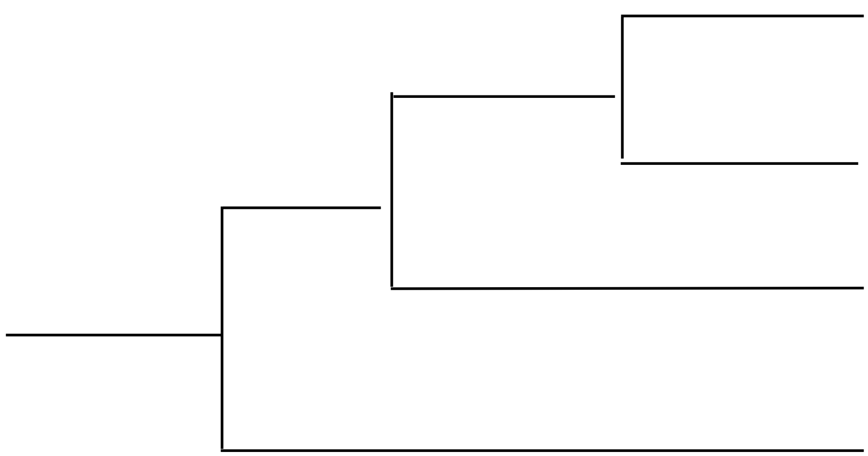
    Early core cooling (injection)

    Late core cooling (recirculation)

- Provides a starting point for more detailed system-level event tree model

Functional Event Tree

Initiating Event	*Reactor Trip*	*Short term core cooling*	*Long term core cooling*	*SEQ #*	*STATE*
IE	*RX-TR*	*ST-CC*	*LT-CC*		



1	*OK*
2	*LATE-CD*
3	*EARLY-CD*
4	*ATWS*

Identify Systems Capable of Fulfilling Functions

- For each initiating event identified
  - Which systems are capable of providing:
    - Reactor subcritical
    - Early core cooling (injection)
    - Late core cooling (recirculation)
- Specific success criteria need to be defined for each system

Success Criteria

IE	Reactor Trip	Short Term Core Cooling	Long Term Core Cooling
Trans	Auto Rx Trip or Man. Rx Trip	PCS or 1 of 3 AFW or 1 of 2 PORVs & 1 of 2 ECI	PCS or 1 of 3 AFW or 1 of 2 PORVs & 1 of 2 ECR
LOCA	Auto Rx Trip or Man. Rx Trip	1 of 2 ECI	1 of 2 ECR

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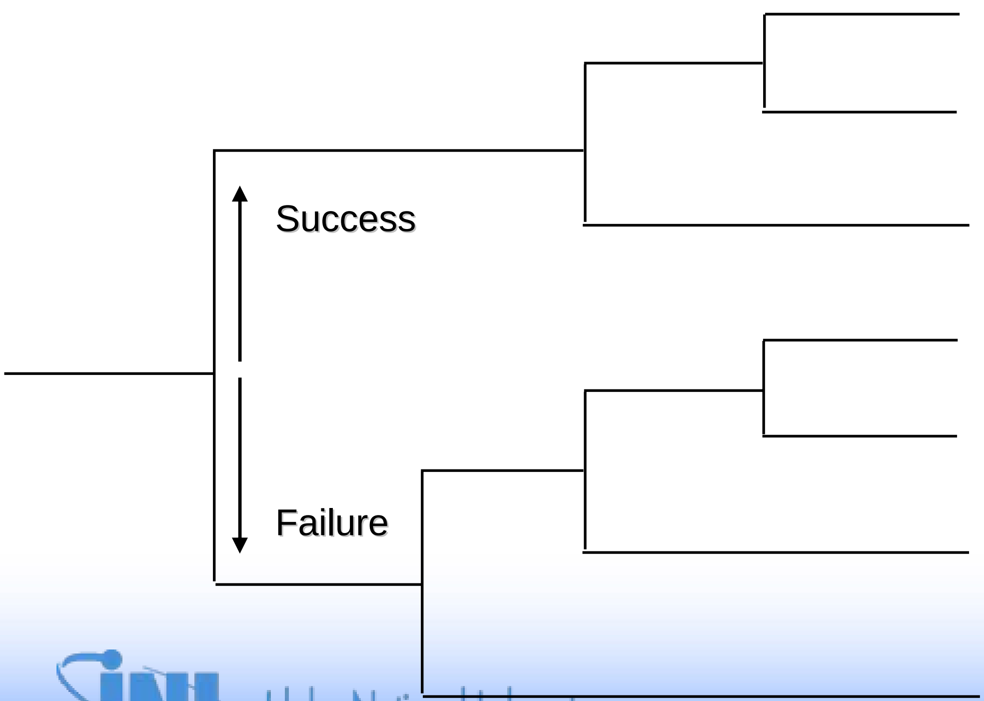
System-Level Event Tree

- Typical ET seen in PRAs
- ET re-drawn after inserting systems as ET top-events
- More top-events consequently more complicated logic
- Unique event tree developed for each initiating event
  - Implies unique plant response to each IE
  - If plant response is not unique, simply combine IE frequencies into a single IE

Accident Sequences From ET

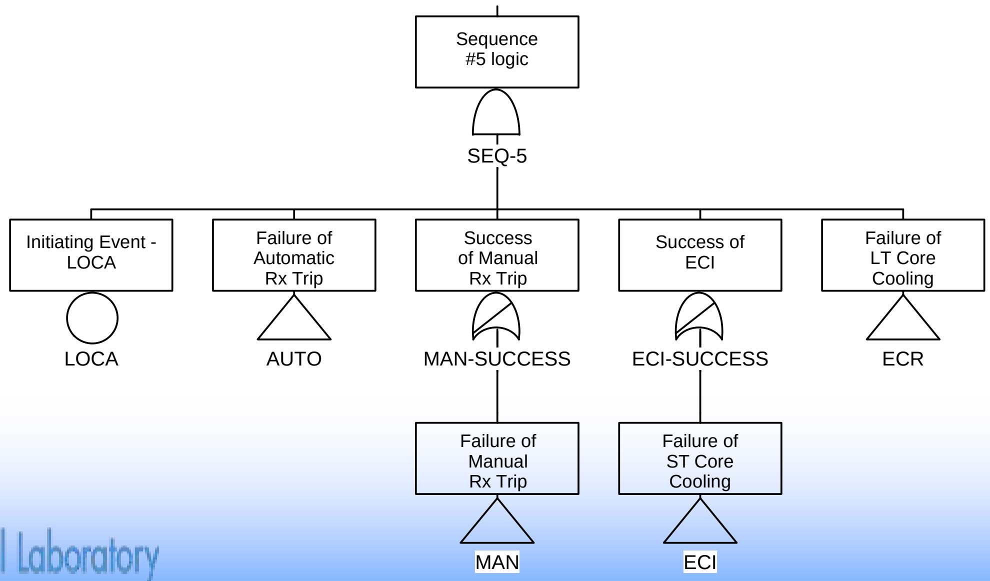
Initiating Event	Rx Trip	Rx Trip	ST Core Cooling	LT Core Cooling	SEQ #	STATE	LOGIC
LOCA	AUTO	MAN	ECI	ECR			



SEQ #	STATE	LOGIC
1	OK	
2	LATE-CD	/AUTO*/ECI*ECR
3	EARLY-CD	/AUTO*ECI
4	OK	
5	LATE-CD	AUTO*/MAN*/ECI*ECR
6	EARLY-CD	AUTO*/MAN*ECI
7	ATWS	AUTO*MAN

Sequence Logic Used to Combine System Fault Trees into Accident Sequence Models

- **System fault trees (or cut sets) are combined, using Boolean algebra, to generate core damage accident sequence models.**
  - **CD seq. #5 = LOCA * AUTO * /MAN * /ECI * ECR**



Sequence Cut Sets Generated From Sequence Logic

- Sequence cut sets generated by combining system fault trees (or cut sets) comprised by sequence logic
- Cut sets can be generated from sequence #5 "Fault Tree"
  - Sequence #5 cut sets = (LOCA) * (AUTO cut sets) * (/MAN cut sets) * (/ECI cut sets) * (ECR cut sets)
  - Or, to simplify (avoid complemented terms) the calculation (via "delete term")
    - Sequence #5 cut sets ≈ (LOCA) * (AUTO cut sets) * (ECR cut sets) - any cut sets that contain (MAN + ECI cut sets)
      - Develop cut set list for: LOCA * AUTO * ECR
      - Develop cut set list for: MAN + ECI
      - Look for item 2 cut sets in item 1 cut sets, and delete them since logically they cannot occur

Delete Term Example

Sequence logic = IE * /Inj * Rec

Inj = P + V1 => /Inj = /P * /V1

Rec = P + V2

Cut sets = IE * (/P * /V1) * (P + V2)

= IE * /P * /V1 * P +

IE * /P * /V1 * V2.

= IE * /P * /V1 * V2.

Cut sets via delete term:

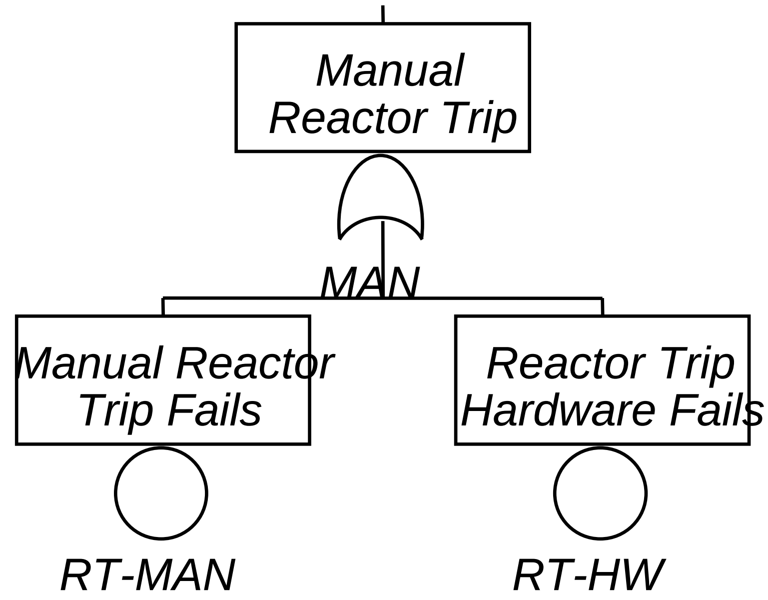
Seq. CS = IE * (P + V2) minus cut sets that contain Inj (failure) cut sets.

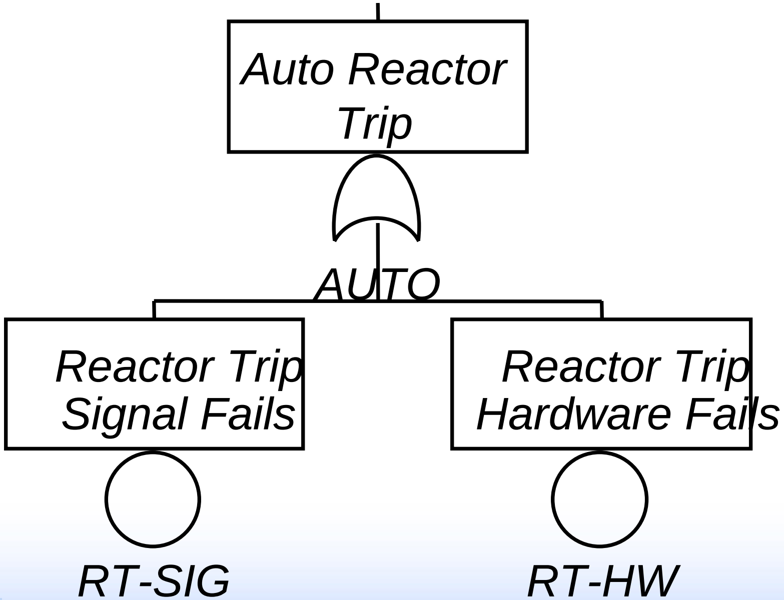
= IE * P + IE * V2 (minus cut sets that contain either P + V1).

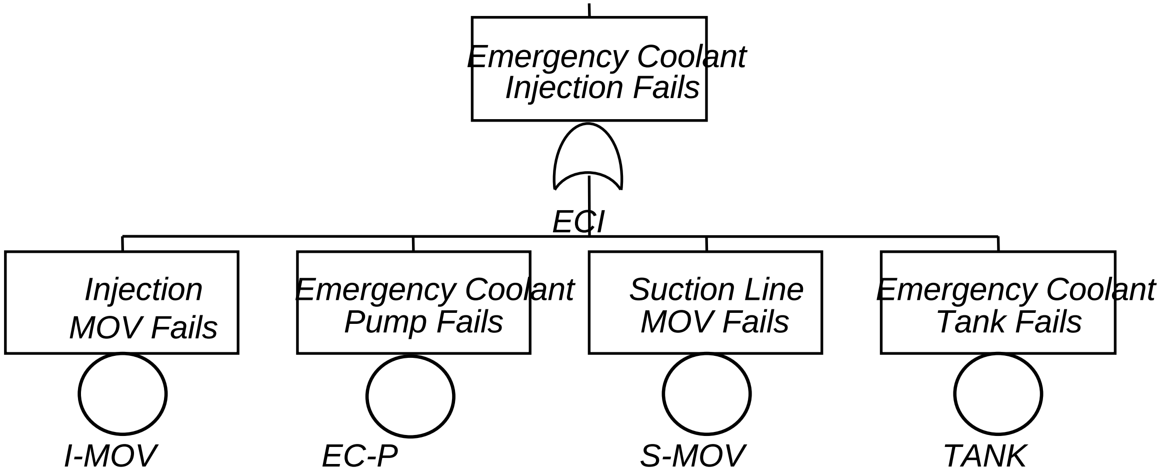
= IE * V2.

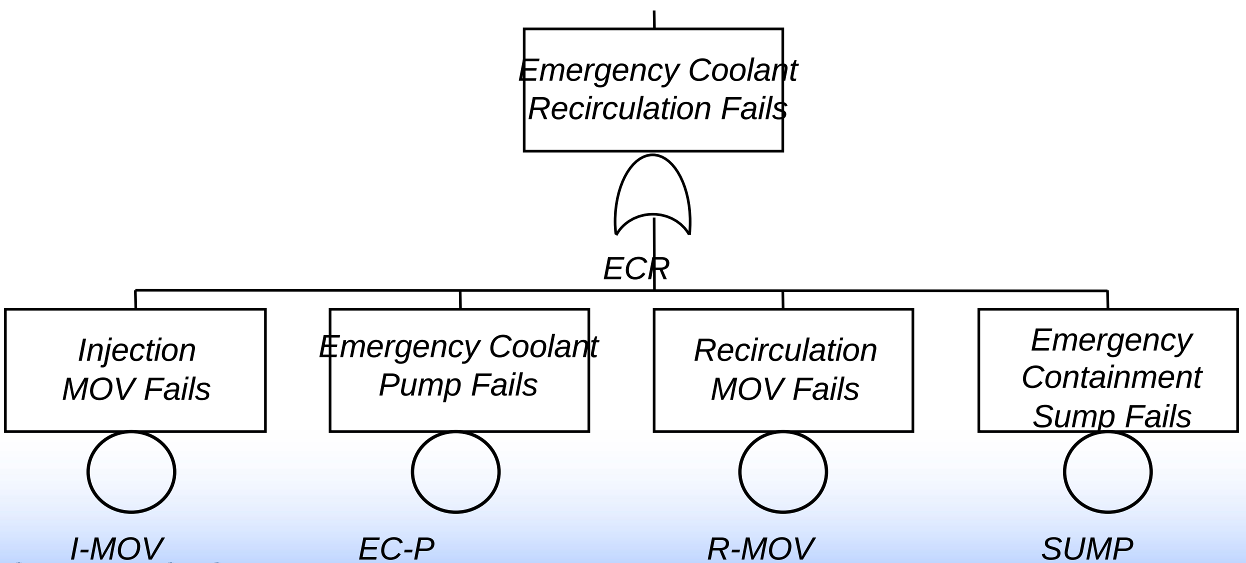
Practice Example:

Generate Cut Sets for Sequence #5






Emergency Coolant Injection Fails
ECI
Injection MOV Fails
Emergency Coolant Pump Fails
Suction Line MOV Fails
Emergency Coolant Tank Fails
I-MOV
EC-P
S-MOV
TANK


Emergency Coolant Recirculation Fails
ECR
Injection MOV Fails
Emergency Coolant Pump Fails
Recirculation MOV Fails
Emergency Containment Sump Fails
I-MOV
EC-P
R-MOV
SUMP

System Modeling Techniques for PRA

Lecture 7 - Common Cause Failure Models

January 2008 – Bethesda, MD

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Objectives

- Understand fundamental theory of CCF modeling
- Become familiar with different CCF models

- Outline
  - Motivation for CCF Models
  - Basic Parameter Model
  - Motivation for Parametric Models
  - Beta-Factor Model
  - Multiple Greek Letter Model
  - Alpha-Factor Model
  - Notes on Analysis Process

Why is CCF Modeling Important?

- Commercial nuclear power plants are designed with safety a priority
  - Redundancy
  - Diversity
  - Defense in depth
- NPP are effectively single failure "proof"
- Only combinations of failures can seriously challenge reactor integrity

Focus on Dependent Failures

- Combinations of independent failures extremely rare events
- Dependent failures pose major challenge to safety
  - Shared equipment and support system dependencies
    - Explicitly modeled in PRA logic
  - Failures of multiple components from a common (or shared) cause
    - Cause not explicitly modeled
    - Treated parametrically – CCF models

Definition of Dependency

Events A and B are said to be *dependent events* if

- $P(A*B) = P(A|B) * P(B)$

  $= P(B|A) * P(A)$

  $\neq P(A) * P(B)$

Typically (not always) if events are dependent

- $P(A*B) > P(A) * P(B)$
  - This is why they are a safety concern

Examples of CCF

- Human interaction
  - Maintenance technician incorrectly sets setpoints on multiple components
  - Incorrect or incorrectly applied lubricant
- Physical or environmental
  - Bio-fouling (e.g., clams, muscles, fish)
  - Design or manufacturing defect
  - Contamination in lubricant or fuel
- Again, not represented explicitly, only parametrically

Basic Parameter Model

- **Background**

  Consider a group of 3 identical components: A, B, and C.

  Notation:

  $A\overline{BC} \equiv$ **Failure of A, success of B and C**

  $AB\overline{C} \equiv$ **Failure of A and B, success of C**

  $ABC \equiv$ **Failure of A, B and C**

  $Q_{XYZ} \equiv$ ***Probability*** **of event XYZ**

  Modeling assumption: Failure probabilities are symmetrical

  $Q_{\overline{AB}C} = Q_{\overline{A}B\overline{C}} = Q_{A\overline{BC}} \equiv Q_1$ (only one component fails)

  $Q_{\overline{A}BC} = Q_{A\overline{B}C} = Q_{AB\overline{C}} \equiv Q_2$ (only two components fail)

  $Q_{ABC} \equiv Q_3$

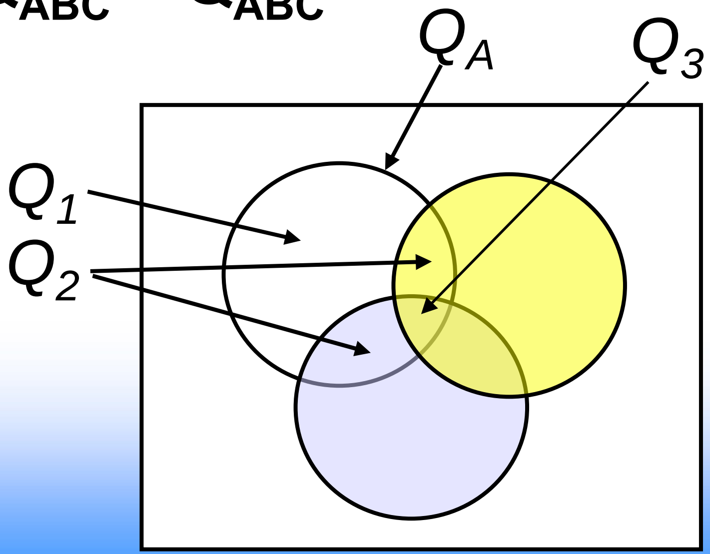
$\overline{X}$ Means component X
Is not failed

Basic Parameter Model

- **Model Parameters**
  - **The Q_k's are <u>system</u> parameters**
    - **They quantify probabilities of system events (CCFs for specific groups of *k* components)**
  - **Relating Q_k's to the total *component* failure rate:**

$$Q_t(A) = Q_A = Q_{A\bar{B}\bar{C}} + Q_{A\bar{B}C} + Q_{AB\bar{C}} + Q_{ABC}$$

$$= Q_1 + 2Q_2 + Q_3$$



Basic Parameter Model

- **Model Parameters**
  - **General expression:** $Q_t = \sum_{k=1}^{m} \binom{m-1}{k-1} Q_k$

    where:

    - **m ≡ number of identical components (size of "common cause component group")**
    - **Q_t ≡ total failure probability for a given component**

Binomial Coefficient:

$$\binom{m-1}{k-1} \equiv \frac{(m-1)!}{(k-1)!(m-k)!} \text{ , (} x! \equiv x * (x - 1) * (x - 2) * .... * 2 * 1)$$

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Motivation for Parametric Models

- Data needed to estimate Q_k in basic parameter model are not generally available
- Available data include:
  - Generic failure probabilities/rates for components (i.e., Q_t)
  - Compilations of dependent failures (without demand data)
- Alternative models use latter information to develop relative fractions of dependent failure events

β -Factor Model

- Originally developed for 2-component systems; later extended to handle larger systems
- Based on notion that component failures can be divided into two groups
  - Those that are independent
  - Those that involve dependent failure of all components

β -Factor Model

Allocation model:

$$Q_t = Q_1 + Q_m = (1 - \beta)Q_t + \beta Q_t$$

Independent contribution

dependent contribution

Therefore:

$$\beta \equiv Q_m/(Q_1+Q_m)$$

β -Factor Estimation

- **In general,**

$$Q_k = \begin{cases} (1-\beta)Q_t & k = 1 \\ 0 & 2 \le k < m \\ \beta Q_t & k = m \end{cases}$$

$$\hat{\beta} = \frac{\sum_{k=2}^{m} kN_k}{\sum_{k=1}^{m} kN_k}$$

where:

N_k is the number of <u>events</u> involving failure of exactly k components so that the product kN_k represents number of failed <u>components</u>.

β -Factor Estimation

Example: Consider a system with two components: A and B.

Component A has failed 3 times in 50,000 hours of service; out of those 3 failure events, 1 event was a common cause failure (involving component B).

Component B also has 50,000 hours of service, and it has failed 2 times (including the joint failure event with A).

β-Factor Estimation

- Point estimates for λ_t and β are then,

  λ_t = 5 failures / 100,000 hr = 5.0 x 10-5/hr

  β = 2/(3+2) = 0.4
- And,

  $\lambda_{CCF} = \lambda_t * \beta$ = 5.0 x 10-5/hr * 0.4

  λ_{CCF} = 2.0 x 10-5/hr
- In the absence of plant-specific data, base component failure rate (λ_t) is obtained from generic failure rates

Multiple Greek Letter (MGL) Model

β - factor extended to treat multiple levels of CCF

Definitions:

$\beta \equiv$ conditional probability that cause of a specific component failure will be shared by one or more additional components

$\gamma \equiv$ conditional probability that common cause failure of a specific component that has failed two components will be shared by one or more additional components

$\delta \equiv$ conditional probability that common cause failure of a specific component that has failed three components will be shared by one or more additional components

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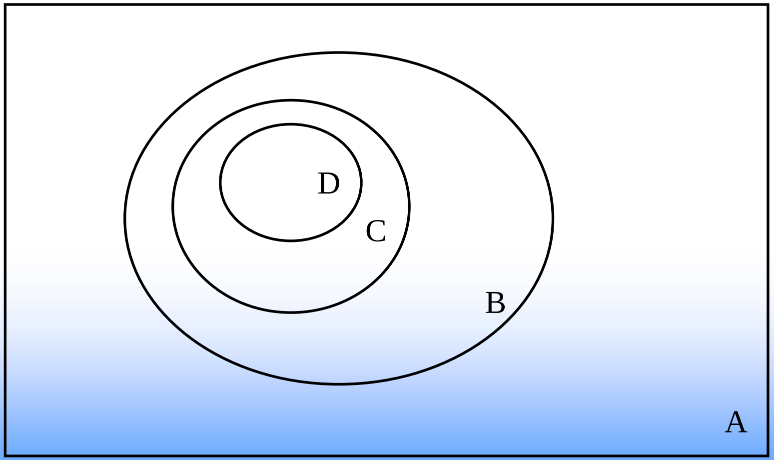
Multiple Greek Letter (MGL) Model

- **Parameters**
  - A: Failures involving component X
  - B: Failures involving CCF of X and at least 1 other component
  - C: Failures involving CCF of X and at least 2 other components
  - D: Failures involving CCF of X and at least 3 other components



β = P(B|A)

γ = P(C|B)

δ = P(D|C)

Multiple Greek Letter (MGL) Model

– **Estimators**

$$\hat{\beta} = \frac{\sum_{k=2}^{m} kN_k}{\sum_{k=1}^{m} kN_k}, \quad \hat{\gamma} = \frac{\sum_{k=3}^{m} kN_k}{\sum_{k=2}^{m} kN_k}, \quad \hat{\delta} = \frac{\sum_{k=4}^{m} kN_k}{\sum_{k=3}^{m} kN_k}$$

N_k is the number of <u>events</u> involving the failure of exactly k components. Therefore, kN_k is the number of failed <u>components</u>.

Multiple Greek Letter (MGL) Model

- **Relations to Q_k's**
  - **m = 3**

$$\hat{\beta} = \frac{2N_2 + 3N_3}{N_1 + 2N_2 + 3N_3}$$

$$\hat{\gamma} = \frac{3N_3}{2N_2 + 3N_3}$$

$$Q_1 = (1-\beta)Q_t$$

$$Q_2 = \frac{1}{2}\beta(1-\gamma)Q_t$$

$$Q_3 = \beta\gamma Q_t$$

  - **m = 4**

$$\hat{\beta} = \frac{2N_2 + 3N_3 + 4N_4}{N_1 + 2N_2 + 3N_3 + 4N_4}$$

$$\hat{\gamma} = \frac{3N_3 + 4N_4}{2N_2 + 3N_3 + 4N_4}$$

$$\hat{\delta} = \frac{4N_4}{3N_3 + 4N_4}$$

$$Q_1 = (1-\beta)Q_t$$

$$Q_2 = \frac{1}{3}\beta(1-\gamma)Q_t$$

$$Q_3 = \frac{1}{3}\beta\gamma(1-\delta)Q_t$$

$$Q_4 = \beta\gamma\delta Q_t$$

α–Factor Model

- **Background**
  - Simple expressions for exact distributions of MGL parameters (accounting for uncertainties) are not always obtainable
  - Approximate methods leading to point estimators provided earlier underestimate uncertainty
  - α-factor model developed to address this issue

α–Factor Model

- **Definition**
  - $\alpha_k \equiv$ **conditional probability that a failure event involves k components failing due to a shared cause, given a failure event**

$$\alpha_k = \frac{\binom{m}{k} Q_k}{\sum_{k=1}^{m} \binom{m}{k} Q_k} \qquad \textit{where} \quad \binom{m}{k} = m!/k!(m-k)!$$

- **Note: This definition emphasizes shocks to the system (i.e., failure events) rather than to the components (i.e., failures)**

α-Factor Model

- **Example (m = 3)**
  - **Failure events involving only 1 component are:**

    $$A\overline{B}\overline{C},\ \overline{A}B\overline{C},\ \overline{A}\overline{B}C$$

  - **Since** $Q_1 = Q_{A\overline{B}\overline{C}} = Q_{\overline{A}B\overline{C}} = Q_{\overline{A}\overline{B}C}$, then $\alpha_1 = \dfrac{3Q_1}{3Q1 + 3Q2 + Q3}$
  - **Similarly,**

    $$\alpha_2 = \frac{3Q_2}{3Q_1 + 3Q_2 + Q_3}$$

    $$\alpha_3 = \frac{Q_3}{3Q_1 + 3Q_2 + Q_3}$$

  - **Note that $\alpha_1 + \alpha_2 + \alpha_3 = 1$ as expected.**

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α-Factor Model

- **Key Expressions**
  - **Point Estimators**

$$\hat{\alpha}_k = \frac{N_k}{\sum_{i=1}^{m} N_i}$$

  - **Expression for Q_k's**

$$Q_k = \frac{k}{\binom{m-1}{k-1}} \frac{\alpha_k}{\sum_{i=1}^{m} i\,\alpha_i} Q_t$$

(from NUREG/CR-5485, page 41, for non-staggered testing)

α-Factor Model

- **Example (m = 3)**
  - **Expression for Q_k's**

$$Q_1 = \frac{\alpha_1}{\alpha_1 + 2\alpha_2 + 3\alpha_3} Q_t$$

$$Q_2 = \frac{\alpha_2}{\alpha_1 + 2\alpha_2 + 3\alpha_3} Q_t$$

$$Q_3 = \frac{3\alpha_3}{\alpha_1 + 2\alpha_2 + 3\alpha_3} Q_t$$

α-Factor Model

Example (m = 3) (cont.)

Relationships with MGL parameters

$$\beta = \frac{2\alpha_2 + 3\alpha_3}{\alpha_1 + 2\alpha_2 + 3\alpha_3}$$

$$\gamma = \frac{3\alpha_3}{2\alpha_2 + 3\alpha_3}$$

$$\alpha_1 = \frac{3(1-\beta)}{3 - \frac{3}{2}\beta - \frac{1}{2}\beta\gamma}$$

$$\alpha_2 = \frac{\frac{3}{2}(\beta - \beta\gamma)}{3 - \frac{3}{2}\beta - \frac{1}{2}\beta\gamma}$$

$$\alpha_3 = \frac{\beta\gamma}{3 - \frac{3}{2}\beta - \frac{1}{2}\beta\gamma}$$

Analysis Process

- General Steps
  1. Starting with system logic model, identify common cause component groups
  2. Develop CCF model
  3. Gather and analyze data
  4. Quantify CCF model parameters
  5. Quantify CCF basic events

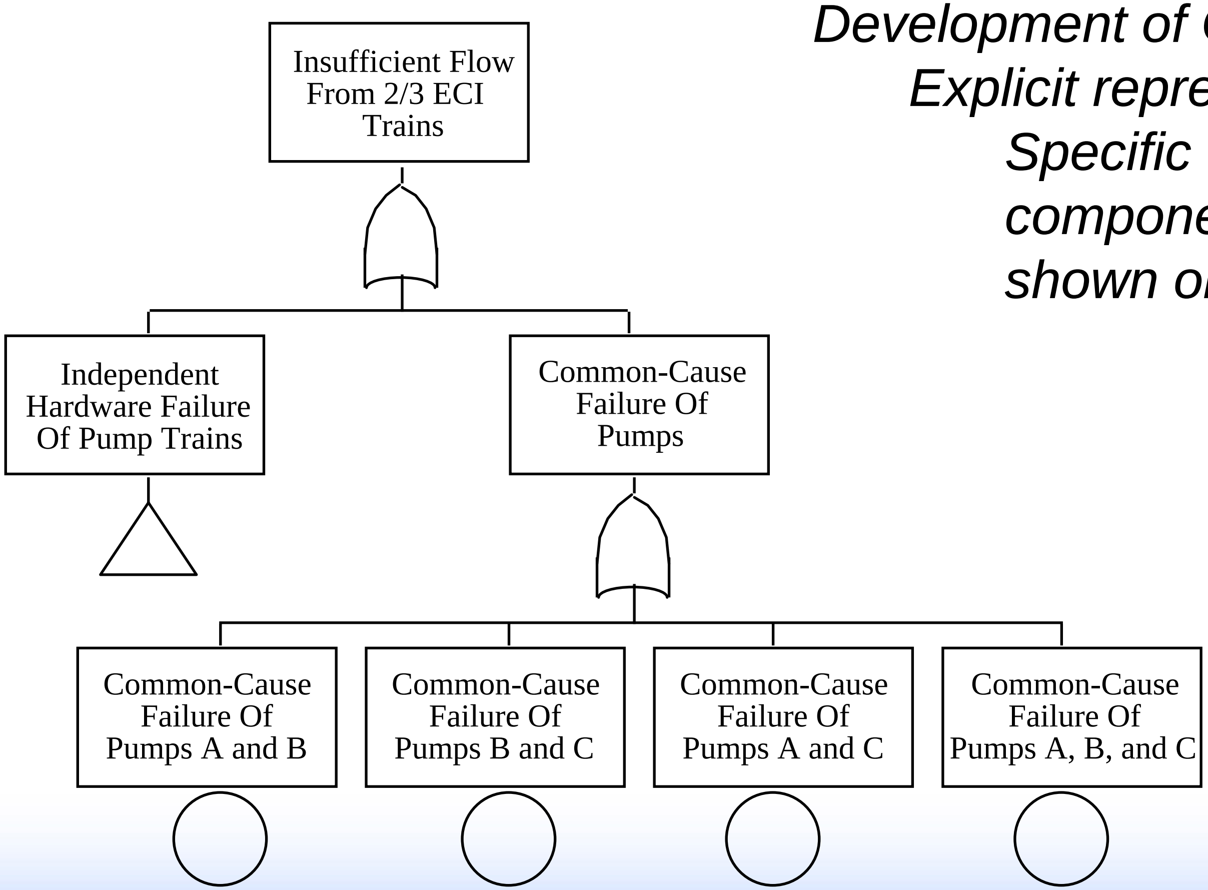
Modeling Process

- "Common Cause Component Groups"
  - Definition: A group of components that has a significant likelihood of experiencing a common cause failure event
  - Consider similarity of:
    - Component type
    - Manufacturer
    - Mode of operation/mode of failure
    - Environment
    - Location
    - Mission
    - Test and Maintenance Procedures

Modeling Process

- "Common Cause Component Groups"
  - Diversity (e.g., in operation, missions) is a possible reason for screening out
    - Note: diverse components can have common piece parts (e.g., common pumps, different drivers)

Modeling Process

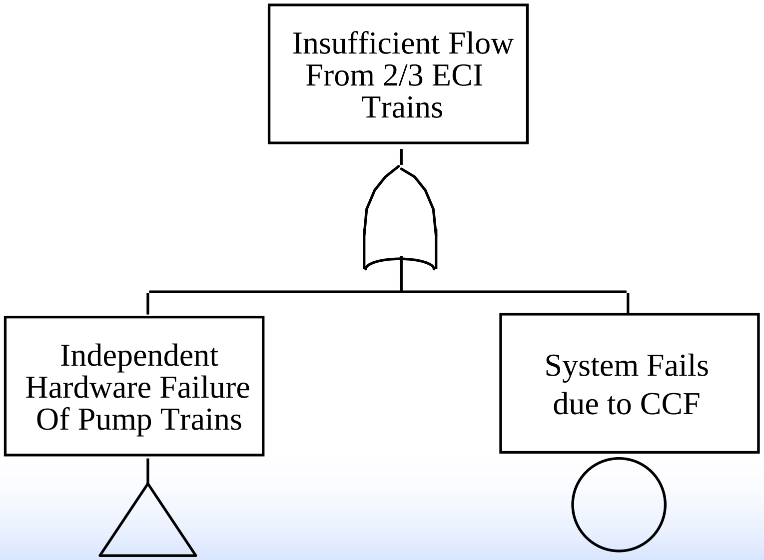


Development of CCF Model

- *Explicit representation example*
  - *Specific combinations of components are explicitly shown on fault tree*

Modeling Process

- Implicit modeling example (3 trains)
  - P(top event due to CCF) = $3Q_2 + Q_3$
  - Probabilities of different combinations are "rolled-up" into the CCF term.



Data Analysis Process

- Data Sources
  - Generic raw data compilations (e.g., LERs, LER summaries, NPE)
  - Plant-specific raw data records (e.g., test and maintenance records, work orders, operator logs)
  - Generic event data and parameter estimates (e.g., NUREG/CR-2770, EPRI NP-3967)
  - NRC/INL CCF database (NUREG/CR-6268)

Data Analysis Process

- **Examines *failure events* (not all demands or success events)**
- **Relatively few failures are clear-cut CCFs**
  - **Demands on redundant components do not always occur simultaneously**
  - **"Failures" are sometimes not demonstrated failures**
    - **Second component inspected and revealed similar degradation/conditions**
- **Interpretation and judgment used to "fill-in" the gaps in the data**
  - ***Degradation Value* technique**
    - **Assigns probabilities for likelihood an event was an actual CCF event**

Data Analysis Process

– **Classification example**

Plant Type (Date)	Event Description	Component Group Size	Degradation Values		
			P_0	P_1	P_2
PWR (12/73)	Two motor-driven AFW pumps were inoperable due to air in common suction line	2	0	0	1

– **Data typically collected include**

- **Component group size**
- **Number of components affected**
- **Shock type (lethal vs. non-lethal)**
- **Failure mode**

Adjusting for System Size

- “Mapping up” and “mapping down” performed for individual p-values
- Algorithms provided in NUREG/CR-4780
- Example: Mapping from m = 3 to m = 2

$$p_0^{(2)} = p_0^{(3)} + \tfrac{1}{3} p_1^{(3)}$$

$$p_1^{(2)} = \tfrac{2}{3} p_1^{(3)} + \tfrac{2}{3} p_2^{(3)}$$

$$p_2^{(2)} = \tfrac{1}{3} p_2^{(3)} + p_3^{(3)}$$

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Adjusting for System Size

– **Example: Mapping from m = 3 to m = 4**
  - **Lethal shock:**

$$p_3^{(3)} = p_4^{(4)}$$

  - **Non-lethal shock:**

$$p_1^{(4)} = \tfrac{4}{3}(1-\rho)\,p_1^{(3)}$$

$$p_2^{(4)} = \rho\, p_1^{(3)} + (1-\rho)\,p_2^{(3)}$$

$$p_3^{(4)} = \rho\, p_2^{(3)} + (1-\rho)\,p_3^{(3)}$$

$$p_4^{(4)} = \rho\, p_3^{(3)}$$

where $\rho \equiv$ conditional probability of a component's failure, given a non-lethal shock.

System Modeling Techniques for PRA

Lecture 8 – Quantification

January 2009 – Bethesda, MD

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INL

Objectives

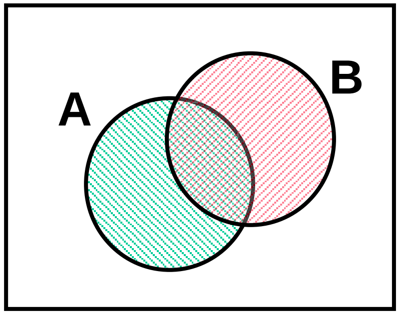
- Understand the process of quantifying cut sets
- Understand value and limitations of different approximations
- Understand impact of correlation of data on quantification results

- Outline
  – Cut set definition
  – Approximations
  – Correlating failure rates

Cut Sets

- **A *cut set* is a combination of events that cause the "top event" to occur**
- **Minimal cut set is the smallest combination of events that causes to top event to occur**
- **Each cut set represents a failure scenario that must be "ORed" together with all other cut sets for the top event when calculating the total probability of the top event**

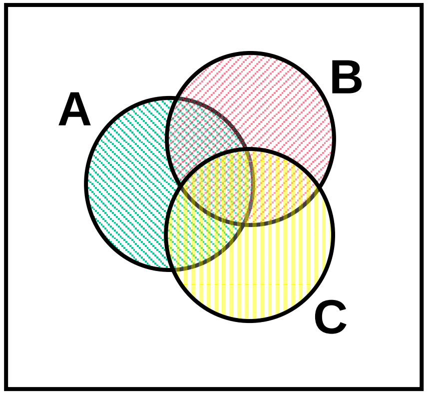
Quantification



- **Exact Solution for Top = A + B:**
  - **P(Top) = P(A + B) = P(A) + P(B) - P(AB)**
- **Cross terms become unwieldy for large lists of cut sets. E.g., if Top = A + B + C, then:**
  - **P(Top) = P(A)+P(B)+P(C)**

    - P(AB)- P(AC)- P(BC)

    + P(ABC)



- **Top events typically quantified using either**
  - **Rare-Event Approximation**

  Or

  - **Minimal Cut Set Upper Bound (min-cut) Approximation**

Rare Event Approximation

- P(Top) = sum of probabilities of individual cut sets

  = P(A) + P(B)
- P(AB) judged sufficiently small (rare) that it can be ignored (i.e., cross-terms are simply dropped)
- In general, for "n" number of cut sets

$$P(\text{Top Event}) \leq \sum_{k=1}^{n} P(MCS_k)$$

Min-Cut Approximation

- P(Top) = 1 - product of cut set success probabilities
  $= 1-[(1 - P(A)) * (1 - P(B))]$ (for two cut sets)
- Assumes cut sets are independent
  – In PRA, cut sets are generally NOT independent
- Generally, $P(\text{Top Event}) \leq 1- \prod_{k=1}^{n} (1-P\{MCS_k\})$
  – If cutsets are not mutually exclusive
    - e.g., complemented or success events

Examples of Cutset Quantification Methods for P(A+B)…Top=A+B

	Small values for P(A) & P(B), A & B independent	Large values for P(A) & P(B), A & B independent	A & B dependent (mutually exclusive)	A & B dependent but not mutually exclusive
Values	P(A) = 0.01 P(B) = 0.03	P(A) = 0.4 P(B) = 0.6	B = /A P(A) = 0.4 P(B) = P(/A) = 0.6	A = C * D B = C * E P(C) = 0.2 P(D) = 0.5 P(E) = 0.5
Exact	0.01 + 0.03 - (0.01 * 0.03) = 0.0397	0.4 + 0.6 - (0.4 * 0.6) = 0.76	0.4 + 0.6 - P(A*/A) = 1.0	= 0.1 + 0.1 – P(CDE) = 0.15
Rare Event	0.01 + 0.03 = 0.04	0.4 + 0.6 = 1.0	0.4 + 0.6 = 1.0	0.1 + 0.1 = 0.2
MinCut UB	1 - [(1-0.01) * (1-0.03)] = 0.0397	1 - [(1-0.4) * (1-0.6)] = 0.76	1 - [(1-0.4) * (1-0.6)] = 0.76	1 – [(1-0.1) * (1-0.1)] = 0.19

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Point Estimates

- Point estimate calculation usually refers to mean values.
  - Result will be approximate mean value
  - For Lognormal mean > median
    - mean/median = $\exp\{1/2[\ln(EF)/z]^2\}$

      (for example: EF = 10, 90% coverage:

      z = 1.645 and mean/median = 2.66)
  - e.g., for median = 1E-3 and EF = 10

    then

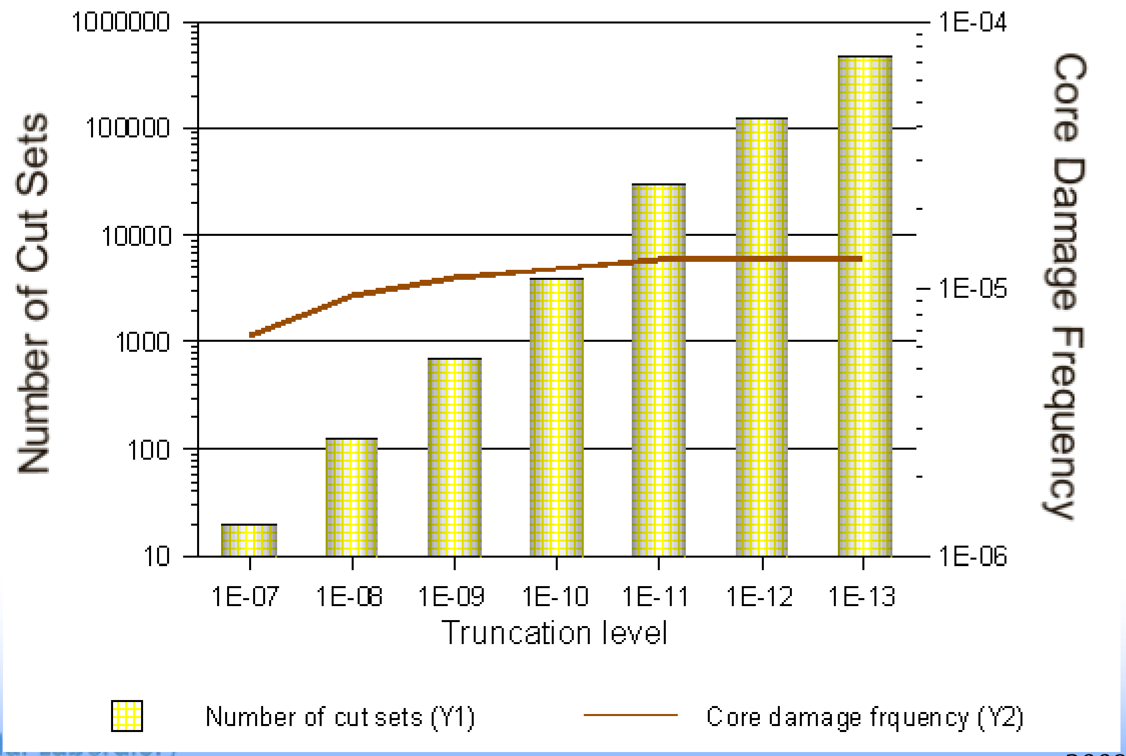
    mean = 1E-3 x 2.66 ≅ 3E-3 (factor of 3 greater than median)

Truncation Issues

- Becoming less of a concern as computer/software increase in capabilities
- Cut set order
  - Truncating on number of basic events in a cut set generally limited to vital area analyses
- Low probability events can accumulate
  - 1,000 cut sets at 1E-9 each = 1E-6
  - 10,000 cut sets at 1E-9 each = 1E-5

Truncation Issues

- **Can affect importance analyses…number of basic events in results increases as truncation decreases**



Correlating Data - Outline

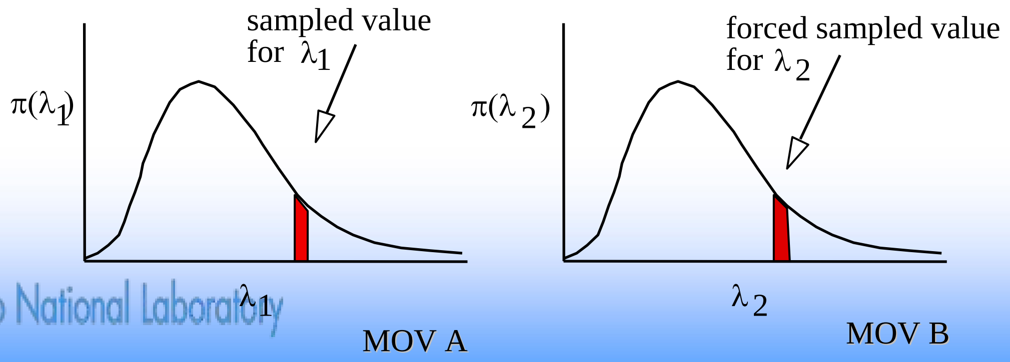
- **What are correlated data?**
  - **Implications on uncertainty results**
- **Combined (either explicitly or implicitly) data can be interpreted in different ways (depending on our assumed model)**
  - **Pooling data to estimate an average or mean occurrence rate**
  - **Models variability among similar individual components/events**
  - **Models variability among different component/event groups**

What are Correlated Data?

- Only an issue when performing uncertainty analysis
- When quantifying a model, does the analyst assume
  - All similar (correlated) events occur at the same rate, or
  - Can occurrence rates vary among similar events?
- Specifically, when performing a simulation quantification (Monte Carlo or Latin Hypercube)
  - Should each simulation run pick a single value, which is applied to all similar events, or
  - Pick a different value for each event?

State of Knowledge Dependencies

- Some sources of dependence
  - Common design/manufacturer
  - Organizational factors (including testing and maintenance quality)
- Treatment (e.g., simple two component system)
  - Identical distributions, completely correlated sampling



Effect on Results

- Correlating data produces wider uncertainty in results
  - Without correlating a randomly selected high value will usually be combined with randomly selected lower values (and vice versa), producing an averaging effect
    - Reducing calculated uncertainty in the result
  - Mean value of probability distributions that are skewed right (e.g. lognormal, commonly used in PRA) is increased when uncertainty is increased

Correlating Failure Rates

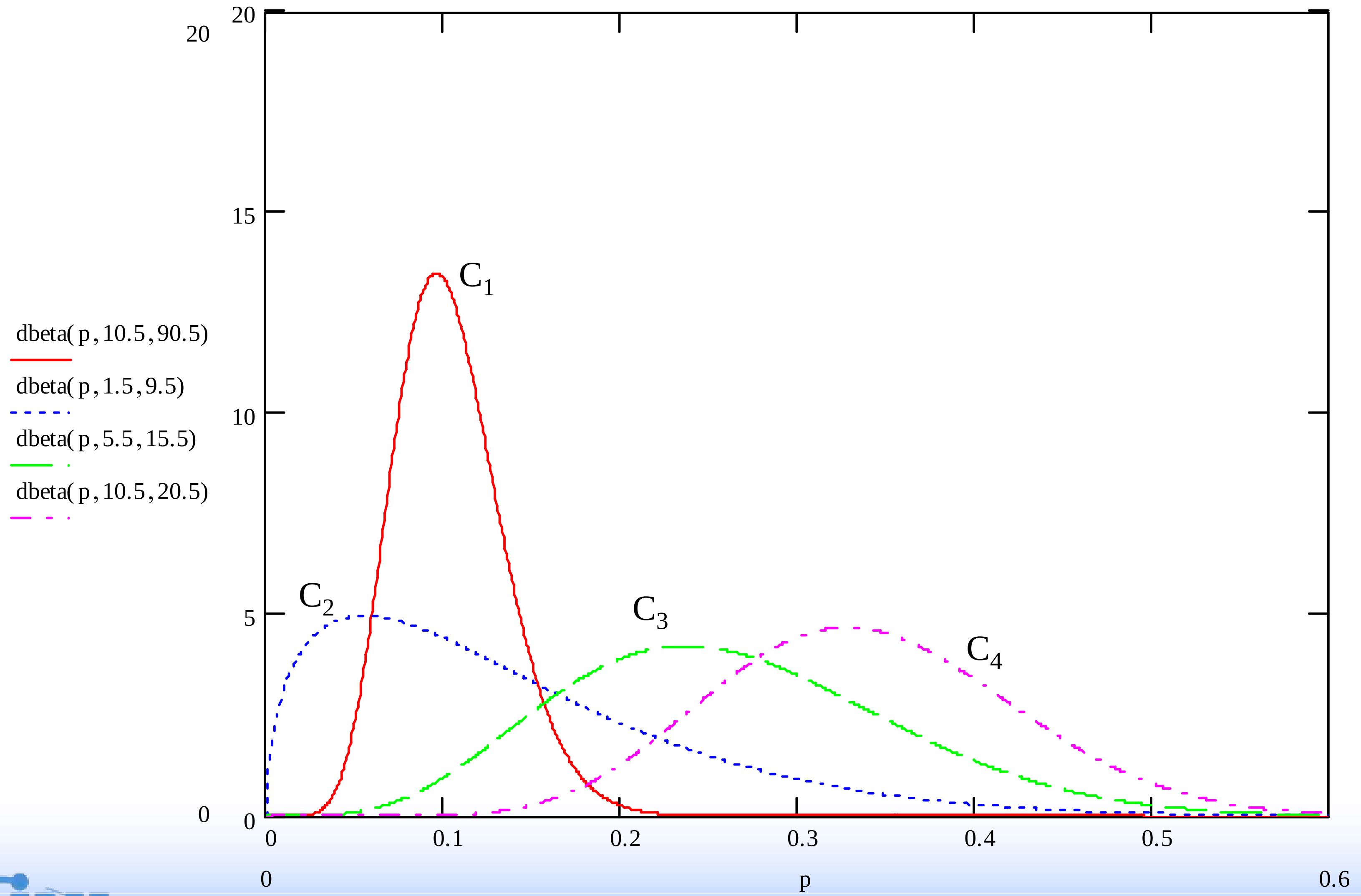
- Important when uncertainties are included in analysis
- Mathematically…
  - $E(\lambda^2) \neq E(\lambda)^2$
  - $E(\lambda^2) = E(\lambda)^2 + Var(\lambda)$
- Simple example:
  - 2 valves, failure of both fails system
  - If $E(\lambda) = 1E\text{-}3$ (mean), EF = 10, and λ is lognormally distributed, then
  - $E(\lambda)^2 = (10^{-3})^2 = 1E\text{-}6$ (uncorrelated)
  - $E(\lambda^2) = (10^{-3})^2 + Var(\lambda) \cong 6E\text{-}6$ (correlated)

When Should Events Be Correlated?

- **Issue illustrated with following example with four nominally identical components**

Component	C_1	C_2	C_3	C_4
Failures	*10*	*1*	*5*	*10*
Demands	*100*	*10*	*20*	*30*

Probability Density Functions (PDFs)



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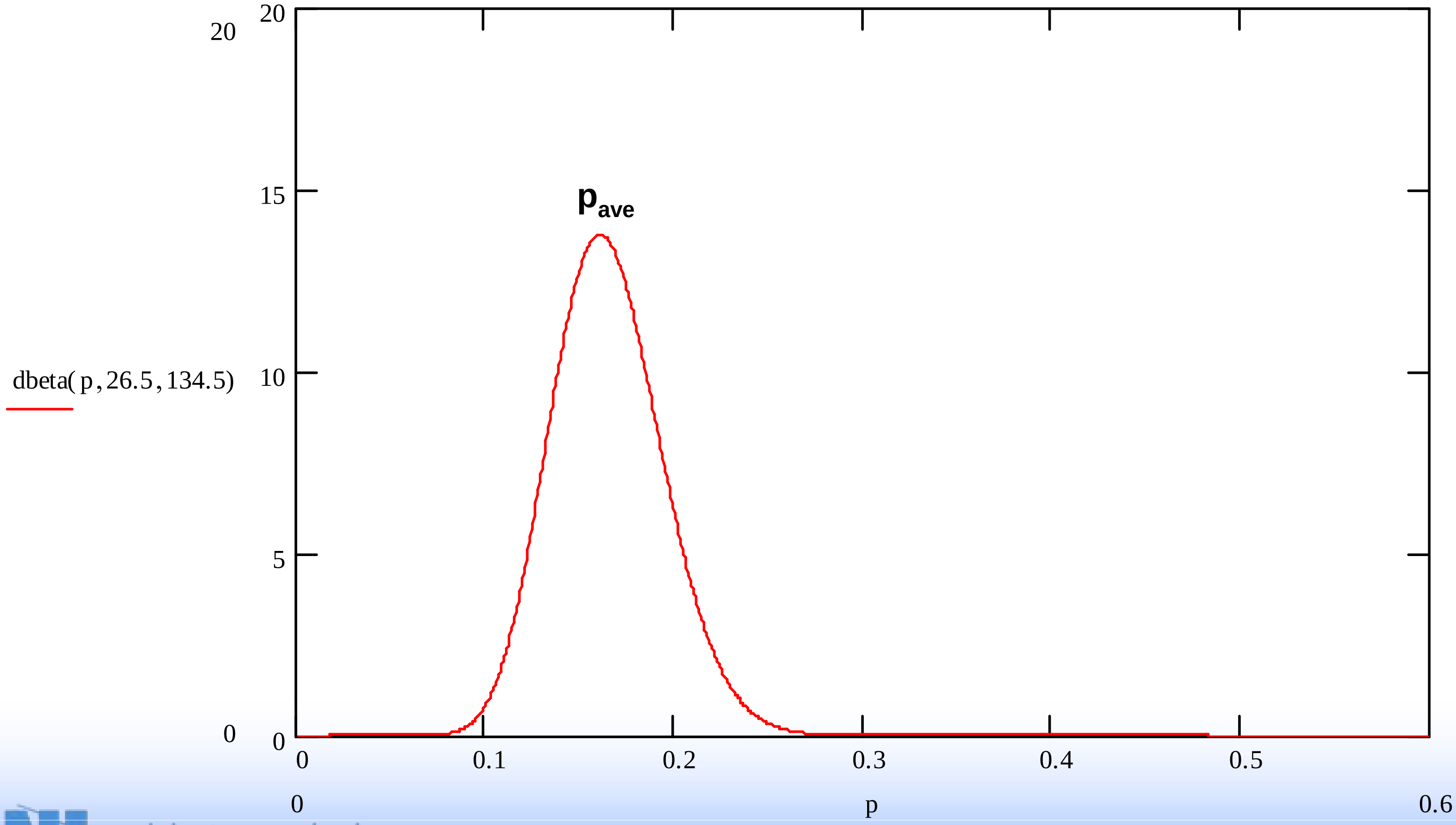
However - Common Situation is to "pool" data for like components

Component	C_1	C_2	C_3	C_4	*Aggregate*
Total Failures					*26*
Total Demands					*160*
Average Failure Probability					*0.16*

Pooled Data Only Provides an Estimate of the Average Probability

- f_t / d_t = p_{ave}
- Effectively, a weighted average of the failure probabilities for C_1, C_2, C_3 and C_4
- Uncertainty associated with p_{ave} represents our knowledge in estimate of p_{ave} (not variability in p_i's)
- More data reduces uncertainty in p_{ave}

Pooling Data Gives Reduced Uncertainty. But, Uncertainty Only Reflects Confidence in Our Estimate of *Average* Failure Rate.



Pooled Data Implies Correlated Failure Rates

- **Used to estimate a single parameter: p_{ave}**
- **Implies $p_1 = p_2 = p_3 = p_4 = p_{ave}$**
- **Assumed model based on existence of a single "true" value for p that describes performance of all similar components (i.e., the C_i's)**
- **Uncertainty a measure of knowledge in p_{ave} estimate**
  - **Therefore, failure rate estimates are correlated**

Desirable Situation

Component	C_1	C_2	C_3	C_4
Failures	10	1	5	10
Demands	100	10	20	30
Failure Probability	0.1	0.1	0.2	0.3

Probability Distribution Reflects Variability in p_i's

- **Component-to-component variability reflects differences in boundary conditions in operation of components**
  - **Different environments, maintenance, wear, manufacturing defects, etc.**
- **Each p_i represents a snapshot of *boundary conditions* any of which are possible for any component**

Specific p_i Can Take on Any Value of p

- Implies: $p_1 \neq p_2 \neq p_3 \neq p_4 \neq p_{ave}$
- Assumed model based on p treated as a random variable that reflects variability in boundary conditions
  - Note that basic Poisson or binomial assumptions are not violated since for any given "experiment" p is assumed to be a constant
- As amount of data increases, uncertainty in p_i's does not decrease (i.e., probability density does not narrow)
- p_i's are not correlated

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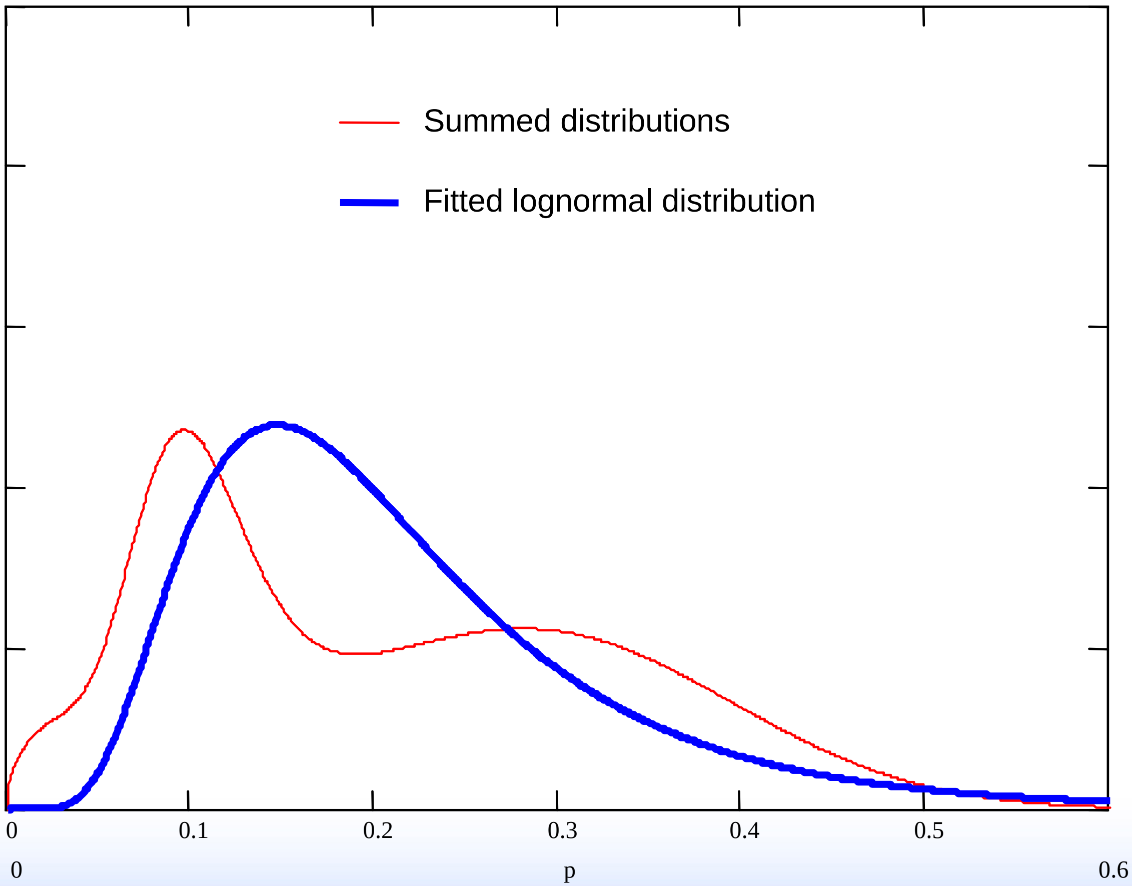
Summing Distributions (Not Data) Captures Variability Among Possible Values of p



Should Not Correlate Samples From PDF That Models Variability

- **Basic Premise: $p_1 \neq p_2 \neq p_3 \neq p_4 \neq p_{ave}$**
- **Uncertainty in distribution reflects variability in components operating conditions and environment**
- **Conditions at one component are NOT related to conditions at another component**
- **Failure rates are NOT correlated**

However

- If
  1. PDF reflects variability among groups, and
  2. Set of components/events consists of a single group (we just don't know which one)

  Then event rates should be correlated
- Example: PDF captures variability among plants, we are modeling a specific plant, once first event rate is chosen, all similar events should use same plant-specific rate

Conclusion

- If PDF on input data reflects knowledge on an average value using pooled data, then should correlate
- If PDF on input data reflects variability or range of possible values, then should not correlate
- If PDF on input data reflects variability or range of groups of values (e.g., plant-to-plant variability), then should correlate (i.e., once a plant is selected the data should be consistent)
- Correlating failure events will generally produce higher system failure probabilities (and higher core damage frequencies)

System Modeling Techniques for PRA

Lecture 9 - Data Analysis

January 2009 – Bethesda, MD

Objectives

- Understand the data requirements of a PRA, including:
  - Implications of modeling assumptions
    - Including Bayesian techniques
  - Potential pitfalls
- Outline
  - PRA Parameters
  - Bayesian Methods
  - Component Failure Rates
  - Component Failure Probability Models
  - Data/Quantification Issues

PRA Parameters

- Initiating Event Frequencies
- Basic Event Probabilities
  - Hardware
    - component unreliability (fail to start/run/operate/etc.)
    - component unavailability (due to test or maintenance)
  - Human Errors (discussed later)
  - Common Cause Failures (already discussed)

Typical Initiating Events

- Only parameter in PRA that is quantified as a frequency
  - General Transients
    - with and without main feedwater
  - LOCAs
    - pipe breaks and stuck open PORVs and SRVs
  - Containment Bypass Event
    - SGTRs and ISLOCAs
  - Support System Failures
    - ac & dc power, SWS, CCW, instrument air

Initiating Event Data

- Typically combination of:
  - Generic data for rare events (e.g., LOCAs)
  - Plant-specific data for more common events (most transients)
- NUREG/CR-5750
  - Contains both plant-specific and industry-wide estimates
  - Three versions available
    - Original: Feb. 1999 (1987-1995)
    - Draft update issued: Mar. 2000 (1987-1998)
    - Electronic data and results updated through 2007

      http://nrcoe.inel.gov/results/
- NUREG/CR-6829 contain industry average rates

Non-IE Basic Events are Probabilities

- Probability of failure depends on mission and failure rate (i.e., the λ or p)
  - Typically modeled as either Poisson or binomial
  - Unavailability (e.g., T&M) calculated directly as a probability
    - However, T&M unavailability can be estimated as an unreliability (like binomial) as well
- Key feature (of data) is that set of failure events and set of demands (or time) must be consistent with each other

Component Failure Rate Estimates

- Point Estimate
  - Demand Failures, Q_d(1 demand) = $\hat{\phi} = f/d$
  - Time related failures
    - Running failure rate, $\hat{\lambda}_r = f_r/t_r$
    - Standby failure rate, $\hat{\lambda}_s = f_s/t_s$
  - Unavailability due to T or M (both scheduled and unscheduled), $Q_{TM} = t_d / t_t$ = down-time/total-time
  - Probability distribution (density functions) on λ's generated using Bayesian methods

Failure Probability Models

- **Demand Failures**
  - **Binomial: prob(r failures in n demands)**

    $$= \binom{n}{r} p^r (1-p)^{n-r}$$

    prob(1 failure|1 demand) = p = Q_d
- **Failures in Time**
  - **Poisson: prob(r failures in time t) = $(1/r!)\, e^{-\lambda t} (\lambda t)^r$**

    prob(r >0, in time t) = $1 - e^{-\lambda t} \approx \lambda t$ (for $\lambda t \ll 1$)

$\binom{n}{r}$ = n!/(r!(n-r)!) = number of ways n items can be grouped r at a time

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Bayesian Methods Employed to Generate Uncertainty Distributions

- Two motivations for using Bayesian techniques
  - Generate probability distributions (classical methods generally only produce uncertainty intervals, not pdf's)
  - Compensate for sparse data (e.g., no failures)
- In effect, Bayesian techniques combine an initial estimate (prior) with plant-specific data (likelihood function) to produce a final estimate (posterior)
- However, Bayesian techniques rely on (and incorporate) subjective judgement
  - different options for choice of prior distribution (i.e., the starting point in a Bayesian calculation)

Bayesian Technique Starts With Subjective Judgement

- **Prior represents one's belief about a parameter before any data have been "observed"**
- **Prior can be either informative or non-informative**
  - **Three common priors**
    - **Non-informative (Jeffreys) prior**
    - **Informative prior (e.g., generic data)**
    - **Constrained non-informative prior**

Non-Informative Prior

- **Imparts little prior belief or information**
- **Minimal influence on posterior distribution**
  - **Except when updating with very sparse data**
- **Basically assumes 1/2 of a failure in one demand (for binomial, or in zero time for a Poisson process)**
  - **If update data is very sparse, mean of posterior will be pulled to 0.5**

E.g.: for plant-specific data of 0/10 (failures/demands)

Update=> 0.5/1 (prior) + 0/10 (likelihood) => 0.5/11 (posterior)

Informative Prior

- **Maximum utilization of <u>all</u> available data**
- **Prior usually based on generic or industry-wide data**
- **Avoids potential conservatism that can result from use of non-informative prior**
- **However, good plant-specific data can be overwhelmed by a large generic data set**

e.g., prior = 100/10000 (failures/demands) = 1E-2

plant-specific = 50/100 (failures/demands) = 0.5

posterior = 150/10100 = 1.5E-2 (basically the prior)

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Constrained Non-informative Prior

- Combines certain aspects of informative and non-informative priors
  - Weights the prior as a non-informative (i.e., 1/2 of a failure)
  - However, constrains the mean value of the prior to some generic-data based value
- For example - generic estimate of previous example would be “converted” to a non-informative prior

100/10000 => 0.5/50 (this then used as the prior)

Update=> 0.5/50 + 50/100 => 50.5/150 = 0.34

Other Update Methods and Priors Exist

- **For Example:**

  Empirical Bayes Method

  Hierarchical Bayes Method

  “Two-Stage” Bayesian Method

  Maximum entropy priors

  Non-Conjugate priors

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System Modeling Techniques for PRA

Lecture 10 - Overview of Human Reliability Analysis for PRA

January 2009 – Bethesda, MD

Objectives

- **Understand HRA as an input to PRA**
- **Understand basic philosophies and techniques in HRA modeling**

- **Outline**
  - **Overview of human contribution in PRA**
  - **Human error classification schemes**
  - **HRA techniques**
  - **HRA limitations and concerns**

Human Reliability Analysis

- Objective
  - Provide input to PRA regarding likelihood of human failure events
- PRA-Based Classification of Human Error (HE)
  - Pre-initiator (latent)
  - Initiating event
  - Post-initiator (dynamic)
  - Recovery
- Contribution from some HE's already accounted for in hardware failure data

HRA Process

- Identify relevant human actions/errors
  - Necessary actions
  - Responses to situation
- Identify influences that affect human performance
  - Stress, time available, training, etc.
- Quantify human error probability
  - Various techniques available

HRA - Error Identification

- PRA model identifies component/system/function failures of interest
- HRA provides additional failure mode information, for example:
  - Maintenance (e.g., failure to restore, miscalibration)
  - Manual actions (e.g., execution of EOPs)
  - Recovery of equipment/functions

Example - Top 10 basic events for Grand Gulf (NUREG-1150 model)

Basic Event	Prob.	FV Import.	Description
RA-LOSP-1HR	1.92E-01	7.18E-01	FAILURE TO RECOVER OFFSITE POWER WITHIN ONE HOUR
RA-DGHW-1HR	9.00E-01	4.69E-01	FAIL. TO RECOVER HARDWARE FAILURE OF A DG WITHIN 1 H
RA-DGMA-1HR	8.00E-01	9.19E-02	FAIL. TO RESTORE A DG FROM A MAINTENANCE OUTAGE W/IN 1 H
ADS-XHE	1.25E-01	5.49E-02	OPERATOR FAILS TO DEPRESSURIZE DURING AN ATWS
RA-DCHW-1HR	5.00E-01	4.97E-02	FAIL. TO RECOVER A BATTERY HW FAILURE WITHIN ONE HOUR
RA-DGCM-1HR	9.00E-01	2.74E-02	FAIL. TO RECOVER A DG COMMON CAUSE FAILURE WITHIN 1 H
RA-LOSP-12HR	1.50E-02	2.65E-02	FAILURE TO RECOVER OFFSITE POWER WITHIN 12 HOURS
RA-RCICDEP-12HR	4.10E-02	1.54E-02	FAILURE TO DEPRESSURIZE RX VIA RCIC STEAM LINE AFTER 12 HRS
FWS-XHE-ALIGN	1.00E+00	1.12E-02	OPERATOR FAILS TO ALIGN FIREWATER SYSTEM FOR INJECTION
RA-FWSACT-12HR	3.00E-02	1.12E-02	FAIL. TO MANUALLY ALIGN AND ACTUATE (LOCAL) THE FWS W/IN 12

Environment/Context Accounted for in HRA Modeling

- **Performance Shaping Factors (PSFs) used to modify basic human error probability**
  - Task Complexity/Workload/Stress
  - Job Aids (e.g., procedures)
  - Training
  - Human-Machine Interface
  - Fitness for Duty
  - Scenario (i.e., specific sequence of events)
  - Organizational Factors

Quantification—Two Levels

- Conservative (screening) level useful for determining which human errors are most significant contributors to overall system error
- Those found to be potentially significant contributors can be analyzed in greater detail (which often lowers the HEP)
  - These revised HEP are then put back into the PRA

Different Techniques Use View Human Errors Differently

- **Classification Approaches**
  - **Omission/Commission**
  - **Skill/Rule/Knowledge**
  - **Slip/Lapse/Mistake/Circumvention**
- **Decomposition Approaches**
  - **None (e.g., Time-Based Methods)**
  - **Functional (e.g., detection/diagnosis/decision and action)**
  - **Task-based**

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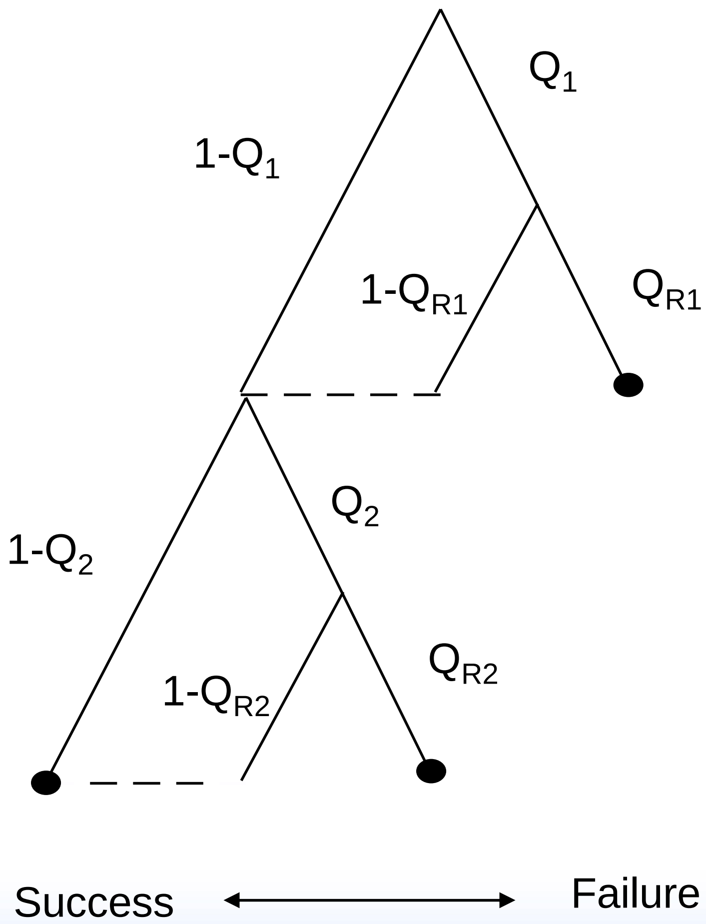
HRA Quantification Techniques

- Screening
  - Accident Sequence Evaluation Program (ASEP)
  - Standardized Plant Analysis Risk HRA (SPAR-H)
- HRA Event Trees
  - Technique for Human Error Rate Prediction (THERP)
- Time Reliability Curves
  - Human Cognitive Reliability (HCR)
- Expert Judgment
  - Success Likelihood Index Method (SLIM)
- Simulator Data

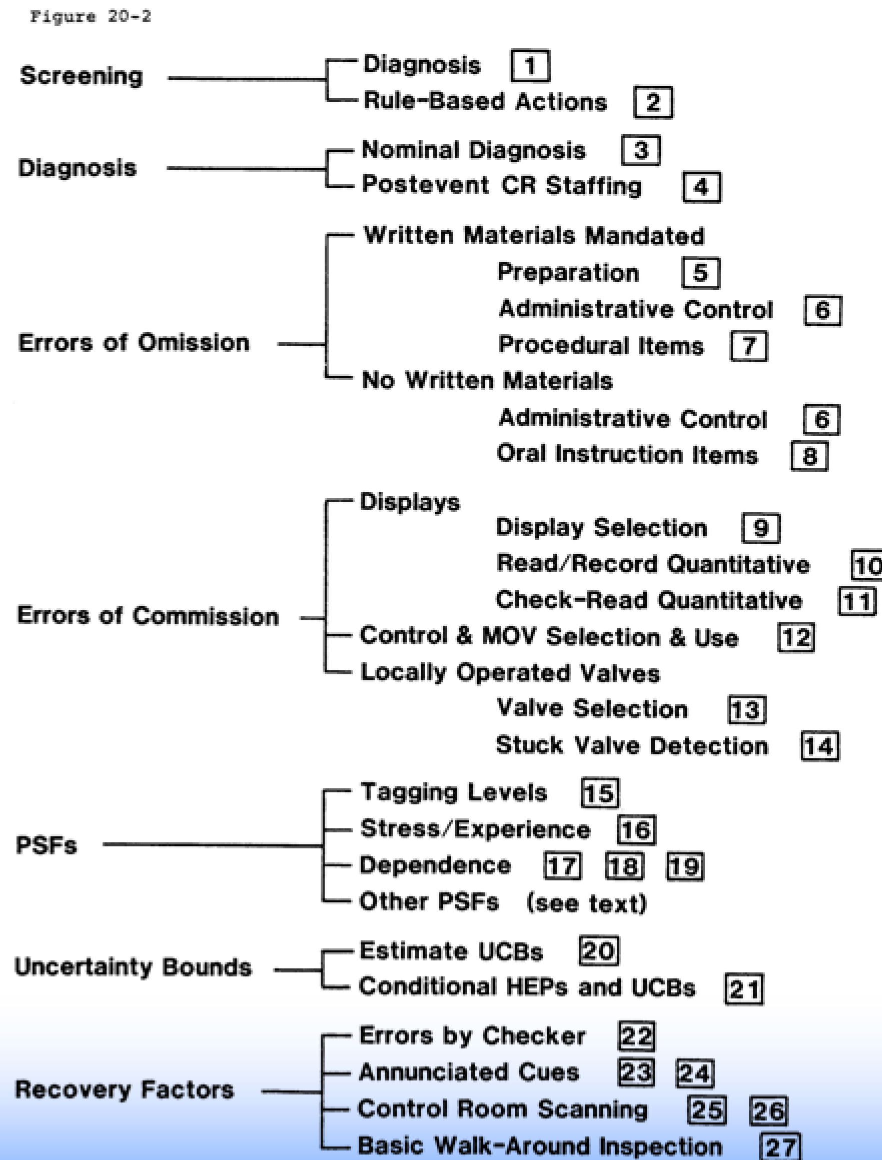
Common HRA Modeling Approaches

- HRA event trees (e.g., THERP)
  - Human actions broken down into individual sub-tasks
- Time Reliability Curve
  - Estimates likelihood of error utilizing ratio of time-available/time-required (to perform some action)
- SPAR-H
  - Simple screening technique developed to support SPAR models
  - Base HEP modified using worksheets

HRA Event Tree (e.g., THERP)



Directory of THERP Tables for Quantification of Human Errors (NUREG/CR-1278)



2009-Jan, page 10-13

Figure 20-2 Quick reference guide to Chapter 20 tables.

Example THERP Table

(Procedural Items - 7)

Table 20-7 Estimated probabilities of errors of omission per item of instruction when use of written procedures is specified* (from Table 15-3)

Item**	Omission of item:	HEP	EF
	When procedures with checkoff provisions are correctly used†:		
(1)	Short list, ≤10 items	.001	3
(2)	Long list, >10 items	.003	3
	When procedures without checkoff provisions are used, or when checkoff provisions are incorrectly used††:		
(3)	Short list, ≤10 items	.003	3
(4)	Long list, >10 items	.01	3
(5)	When written procedures are available and should be used but are not used††	.05‡	5

*The estimates for each item (or perceptual unit) presume zero dependence among the items (or units) and must be modified by using the dependence model when a nonzero level of dependence is assumed.

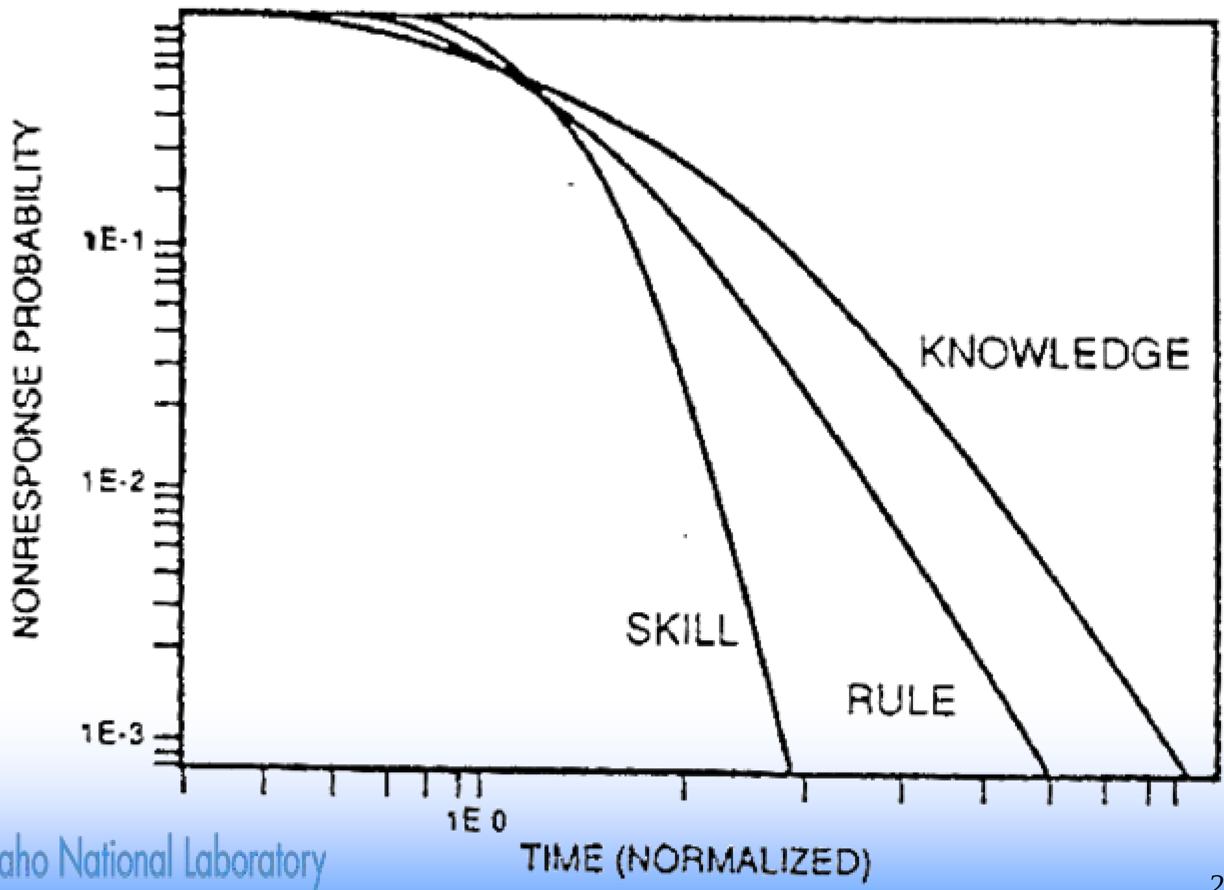
**The term "item" for this column is the usual designator for tabled entries and does not refer to an item of instruction in a procedure.

†Correct use of checkoff provisions is assumed for items in which written entries such as numerical values are required of the user.

††Table 20-6 lists the estimated probabilities of incorrect use of checkoff provisions and of nonuse of available written procedures.

‡If the task is judged to be "second nature," use the lower uncertainty bound for .05, i.e., use .01 (EF = 5).

HCR Model Categorizes Actions as Knowledge, Rule or Skill Based



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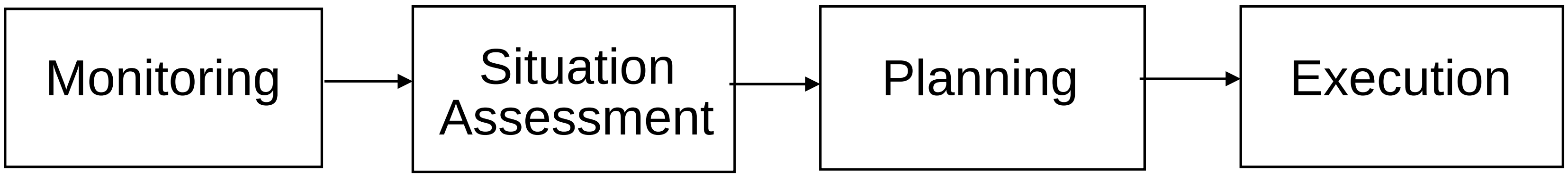
HRA Developed to Support SPAR Models – SPAR-H

- **Method is somewhat screening (i.e., not a detailed HRA, but not overly conservative either)**
- **Each human task classified as diagnosis, action, or both**
- **Eight PSFs considered**
- **Includes provision for factoring in the effect of dependencies between operator actions**
- **HRA process comprises a 3-page worksheet for each human action analyzed**

HRA Modeling Concerns

- **Role of Cognition**



  - **Provides causal factors for specific "errors of commission," dependencies between failure events**
  - **Heavily influenced by scenario context, but how to identify or quantify a specific context?**

HRA Modeling Concerns (cont.)

- Role of Teamwork
  - What is the relative influence of factors defining "good teamwork"?
  - Is an explicit model required?
- Management and Organizational Factors
  - What is the relative influence of factors characterizing management and organization?
  - Is an explicit model required?
  - Where should the analysis boundaries be drawn?

HRA Modeling Concerns (cont.)

- HRA data is very limited
  - Little experience data available
  - THERP is based on 1960's data from assembling nuclear weapons
  - HCR based on simulator experiments
    - Operators are expecting something to happen
    - Would operators really perform the same in an actual emergency situation?

System Modeling Techniques for PRA

Lecture 11 - Risk Assessment Results

January 2009 – Bethesda, MD

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Objectives

- Be able to understand typical PRA results
- Understand value and limitations of importance factors

- Outline
  - Dominant Contributors
  - Importance Measures

Sample Summary Level 1 Results

Plant	Study Sponsor	Method	No. of Dominant Sequences	%CDF
Beaver Valley 2	Utility	ET/BC	12	42
Brunswick 1	Utility	Linked FT	10	95
Brunswick 2	Utility	Linked FT	10	95
Dresden	Utility	ET/BC	10	95
Farley	Utility	ET/BC	19	35
FitzPatrick	Utility	ET/BC	9	87
Grand Gulf	USNRC	Linked FT	3	96
La Salle	USNRC	Linked FT	5	95
Oyster Creek	Utility	ET/BC	10	51
Peach Bottom	USNRC	Linked FT	11	95
Sequoyah	USNRC	Linked FT	15	95
Surry	USNRC	Linked FT	20	95
Zion	USNRC	ET/BC	13	95

Sample Summary Level 1 Results

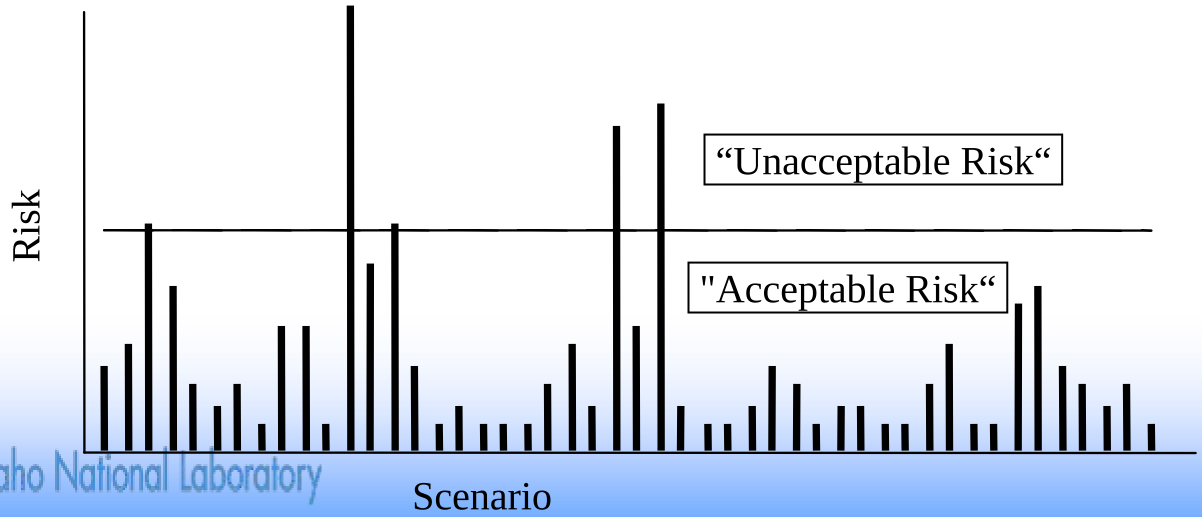
Westinghouse PWR

BWR

19	SBO - Battery Depletion	1.1	94.5
20	SBO - Stuck Open PORV	0.8	95.3

Dominant Contributors

- Implications
  - Typically small number of scenarios
  - Can concentrate on a small number of issues
  - As outliers are addressed, more scenarios become the "important" contributors



Dominant Contributors

- Contributors to risk can be identified at many levels
  - Initiating events (e.g., LOCA)
    - Sum of all CD sequences with particular IE
  - Accident sequences (e.g., S5 = LOCA * AUTO * /MAN * /ECI * ECR)
  - Minimal cut sets (e.g., ECI = PS-A * PS-B)
  - Failure causes (e.g., CCF of PS-A and PS-B)

What are Importance Measures

- A means of utilizing a PRA model to measure impact of model inputs on total risk
  - An effective way to separate, identify, & quantify values of individual factors which affect risk
    - Design features
    - Plant operations
    - Test & maintenance
    - Human reliability
    - System & component failures

Importance Measures

- Provide quantitative perspective on dominant contributors to risk and sensitivity of risk to changes in input values
- Usually calculated at core damage frequency level
- Common importance measures include:
  - Fussell-Vesely
  - Risk Reduction or Risk Reduction Worth
  - Risk Increase or Risk Achievement Worth (RAW)
  - Birnbaum

Fussell-Vesely (FV)

- Measures the overall percent contribution of cut sets containing a basic event of interest to the total risk
- Calculated by finding the value of cut sets that contain the basic event of interest (x_i) and dividing by the value of all cut sets representing the total risk

$$FV_{xi} = F(i) / F(x)$$

or alternate equations

$$FV_{xi} = [F(x) – F(0)] / F(x) = 1 - F(0) / F(x) = 1 – 1/RRR_{xi}$$

where,

F(x) is the total risk from all cut sets with all basic events at their nominal input value

F(i) is the total risk from just those cut sets that contain basic event x_i

F(0) is the total risk from all cut sets with basic event of interest (x_i) set to 0

- The FV range is from 0 to 1 (0% to 100%)

Example: If a basic event such as check valve A (CVA) appears in minimal cut sets contributing 2×10^{-6} to CDF and the total CDF from all minimal cut sets is 1×10^{-5}, then the $FV_{CVA} = (2 \times 10^{-6})/(1 \times 10^{-5}) = 0.2$ (20%)

Risk Reduction Importance (Risk Reduction Worth)

- Measures the amount that the total risk would decrease if a basic event's input value were 0 (i.e., never fails)
- Calculated as either ratio or difference between the value of all cut sets representing the total risk with all basic events at their nominal input value and the value of the total risk with the basic event of interest (x_i) set to 0

  Ratio: $RRR_{xi} = F(x) / F(0)$

  Difference (or Interval): $RRI_{xi} = F(x) - F(0)$

  where,

  F(x) is the total risk from all cut sets with all basic events at their nominal input value

  F(0) is the total risk from all cut set with basic event of interest (x_i) set to 0
- The Risk Reduction Ratio range is from 1 to ∞
- Risk Reduction gives the same ranking as Fussell-Vesely
- For Maintenance Rule (10 CFR 50.65), NUMARC Guide 93-01 (endorsed by NRC) uses a RRR significance criterion of 1.005 (which is equivalent to Fussell-Vesely importance of 0.005)

  Example: If a basic event such as check valve A (CVA) results in a CDF of 3×10^{-6} when not failed and total CDF from all minimal cut sets is 1×10^{-5}, then the $RRR_{CVA} = (1\times10^{-5})/(3\times10^{-6}) = 3.33$

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Risk Increase Importance (Risk Achievement Worth)

- Measures the amount that the total risk would increase if a basic event's input value were 1 (e.g., component is failed or taken out of service)
- Calculated as either ratio or difference between the value of the total risk with the basic event of interest (x_i) set to 1 and the total risk with all basic events at their nominal input value

  Ratio: RAW_{xi} or RIR_{xi} = F(1) / F(x)

  Difference (or Interval): RII_{xi} = F(1) - F(x)

  where,

  F(x) is the total risk from all cut sets with all basic events at their nominal input value

  F(1) is the total risk with basic event of interest (x_i) set to 1
- Ratio measure referred to as Risk Achievement Worth (RAW)
- The RAW range is ≥ 1
- For Maintenance Rule (10 CFR 50.65), NUMARC Guide 93-01 (endorsed by NRC) uses a RAW significance criterion of 2

  Example: If a basic event such as check valve A (CVA) results in a CDF of 2×10^{-5} when failed and the total CDF from all minimal cut sets is 1×10^{-5}, then the $RAW_{CVA} = (2\times10^{-5})/(1\times10^{-5}) = 2$

Birnbaum (B)

- Measures the rate of *change* in total risk as a result of changes to the input value of an individual basic event
- Ranks events according to the effect they produce on the risk level when they are modified from their nominal values

  $B_x = \partial F(x) / \partial x$

  where,

  F(x) is the total risk from all cut sets with all basic events at their nominal input value

  $\partial / \partial x$ is the first derivative of the risk expression with respect to the basic event of interest (x_i)

- When the risk expression has a linear form

  $B_{xi} = F(1) - F(0)$

  where,
  F(1) is the total risk with basic event of interest (x_i) set to 1
  F(0) is the total risk from all cut set with basic event of interest (x_i) set to 0

- When the risk expression has a linear form
- The B range is > 0 (i.e., small B indicates little risk sensitivity and large B indicates large risk sensitivity)

  Example: If a basic event such as check valve A (CVA) results in a CDF of 3×10^{-6} when not failed and results in a CDF of 2×10^{-5} when failed, then the $B_{CVA} = (2\times10^{-5}) - (3\times10^{-6}) = 1.7\times10^{-5}$

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Application Notes

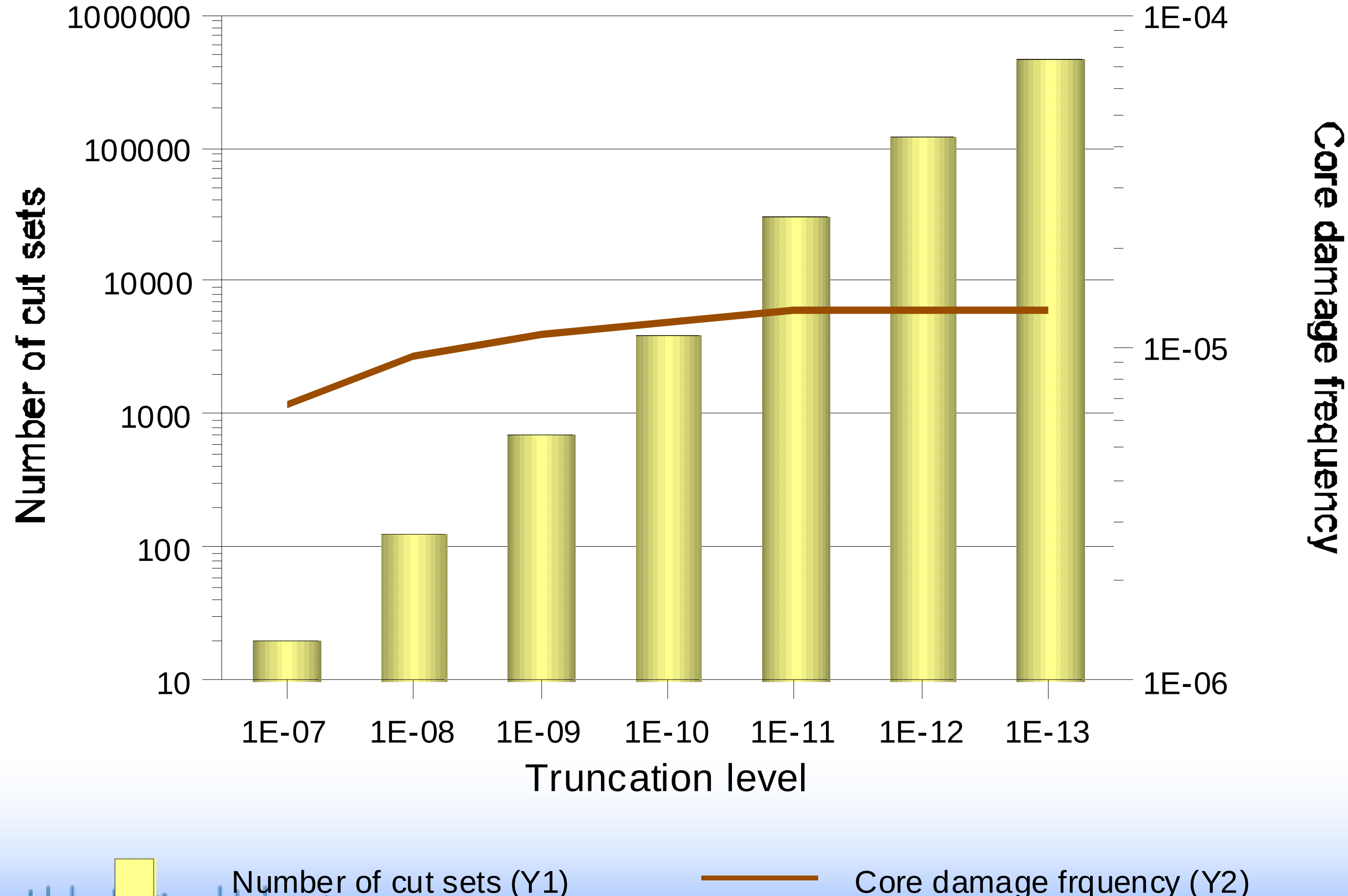
- Relations between measures
  - $FV = 1 - 1/RRR_i$
  - $Br_i \cong F_i(1) = F(x) + RII_i$

    [if $F_i(0) << F_i(1)$]
- Measures can be computed for systems and components as well as basic events
  - Concerns about how to computationally generate these (i.e., importance measures generally do not "add" due to overlap between cut sets)

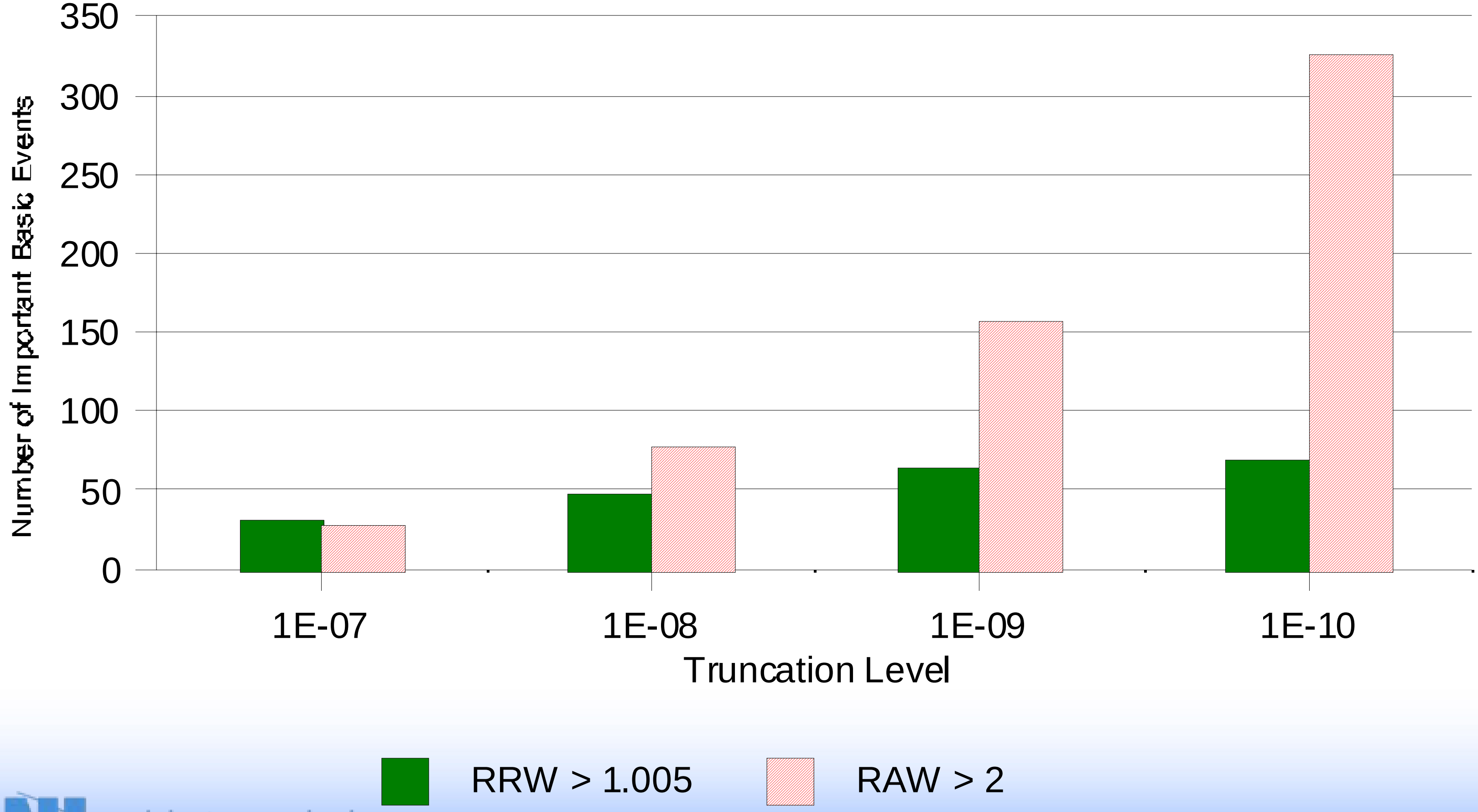
Application Notes (cont.)

- Cautions
  - Improper/misleading labeling of basic events
  - Exclusion of components not in model (e.g., passive components)
  - Parameter values used for other events in model
  - Present configuration of plant (equipment that is already out for test/maintenance)
  - Model truncation during quantification and the affect on Birnbaum and RAW

Core Damage Frequency and Number of Cut Sets Sensitive to Truncation Limits



Truncation Limits Affect Importance Rankings



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System Modeling Techniques for PRA

Lecture 12 - Special Topics

January 2009 – Bethesda, MD

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Objectives

- General understanding of special topics and issues associated with PRA

- Outline
  - Recovery Analysis
  - Level 2 and Level 3
  - Aging
  - External Events

Recovery Analysis Required for Realistic Estimate of Risk

- Options are typically available to control room operators for recovering from component/system failures
  - Manually actuating equipment
  - Re-aligning flow around failed equipment
  - Cross-tie systems from “other” unit
  - Utilizing non-safety grade equipment
- Typically quantified using detailed HRA

Recovery Analysis (cont.)

- Ideally treated at cut set specific level
- Specific set of basic events (in cut set) examined to identify potential recover actions
  - Incorporating into system models usually not a good idea (can create situations of multiple recovery actions in same scenario; can result in impossible recovery actions)
- Recovery possibilities can depend on specific failure modes and mechanisms
  - e.g., HPI MDP fails to start due to actuation failure, can be recovered via manual start (mechanical FTS might not be recoverable)

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Level 2/3 Analysis

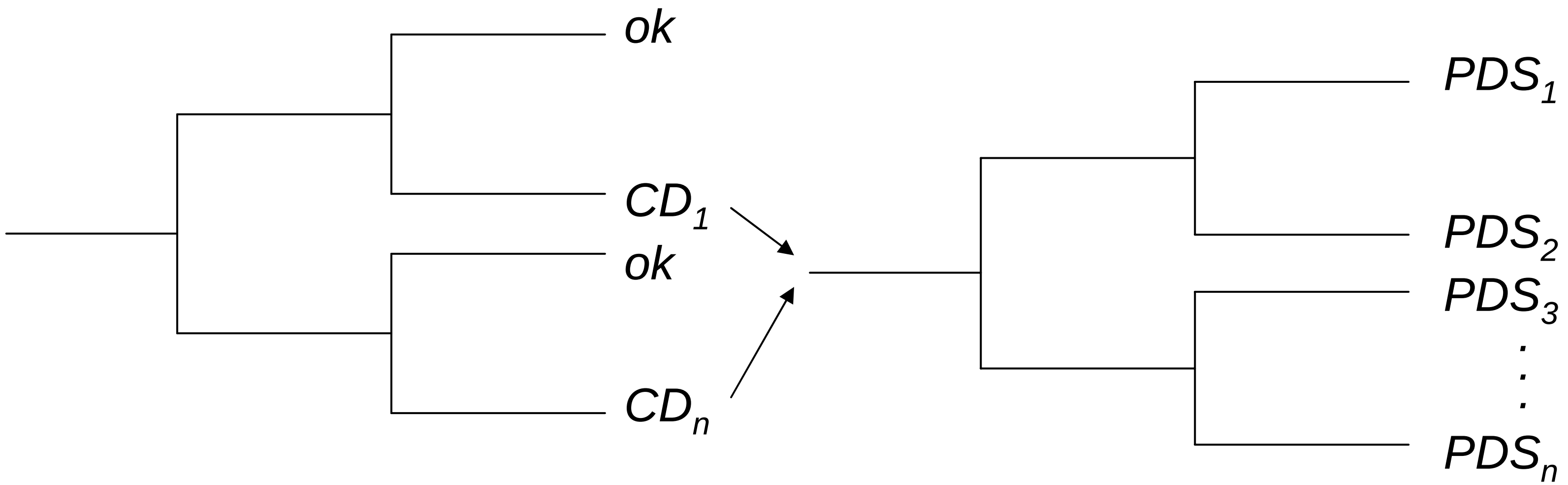
- **Level-1 accident sequences analysis typically quantifies core damage frequency (CDF)**
- **Containment analysis (Level 2) and consequence analysis (Level 3) usually performed "separate" from CDF analysis**
- **Method needed to link accident sequence analysis to containment analysis**

Expanded Systems Analysis Needed to Support Level-2 Model

IE *Level-1 Event Tree*

Bridge Event Tree Appends Containment Systems to Level-1 ET

<u>IEs</u>
RxTrip
LOCA
LOSP
SGTR
etc.



Bridge Event Trees

- **Additional system models and analyses needed before containment analysis can be performed**
  - **"Core Damage" result, not adequate for starting containment analysis**
  - **Containment system models need to be integrated with Level 1 system analysis (i.e., need to capture dependencies)**
  - **Bridge Event Tree (BET) used to model additional systems/phenomena, linked to Level 1 event trees**
    - **Typically generates Plant Damage State (PDS) vectors**

Plant Damage States

- Output (end states) of BET defined in terms of specific details on CD accident sequence
- Method utilizes a vector framework
  - e.g., ACCBABDC
  - Each character identifies the status of a particular system or event
  - Vector is “read” by the Level 2 analysis

Example Plant Damage State Vector Framework

Character	PWR	BWR
1	Status of RCS at onset of core damage	Status of RPS
2	Status of ECCS	Status of electric power
3	Status of containment heat removal	RPV integrity
4	Status of electric power	RPV pressure
5	Status of contents of RWST	Status of HPI
6	Status of heat removal from S/Gs	Status of LPI
7	Status of cooling for RCP seals	Status of containment heat removal
8	Status of containment fan coolers	Status of containment venting
9		Level of pre-existing leakage from containment
10		Time to core damage

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Palisades IPE PDS Characteristics

#	Characteristic	Description
1	*Initiator*	*Affects potential for containment bypass, fission product retention by the RCS, pressure of the RCS at vessel failure, etc.*
2	*CD Time*	*Time of fission product release and amount of warning time for offsite protective actions.*
3	*Secondary Cooling*	*Can affect late revaporization of fission products retained in the RCS*
4	*Pressurizer PORV*	*Affects RCS pressure during the core relocation/vessel failure phase of a CD sequence*
5	*Containment Systems*	*Affect long term integrity of containment. Can affect debris coolability, flammable gas behavior, fission product releases*

Palisades IPE PDS Character #1 (Initiator)

ID	*Description*
A1	*Large LOCA (d > 18 in.)*
A2	*Medium LOCA (2 in. < d < 18 in.)*
B	*Small LOCA (1/2 in. < d < 2 in.)*
C	*Interfacing System LOCA*
D	*SGTR*
T	*Transient*

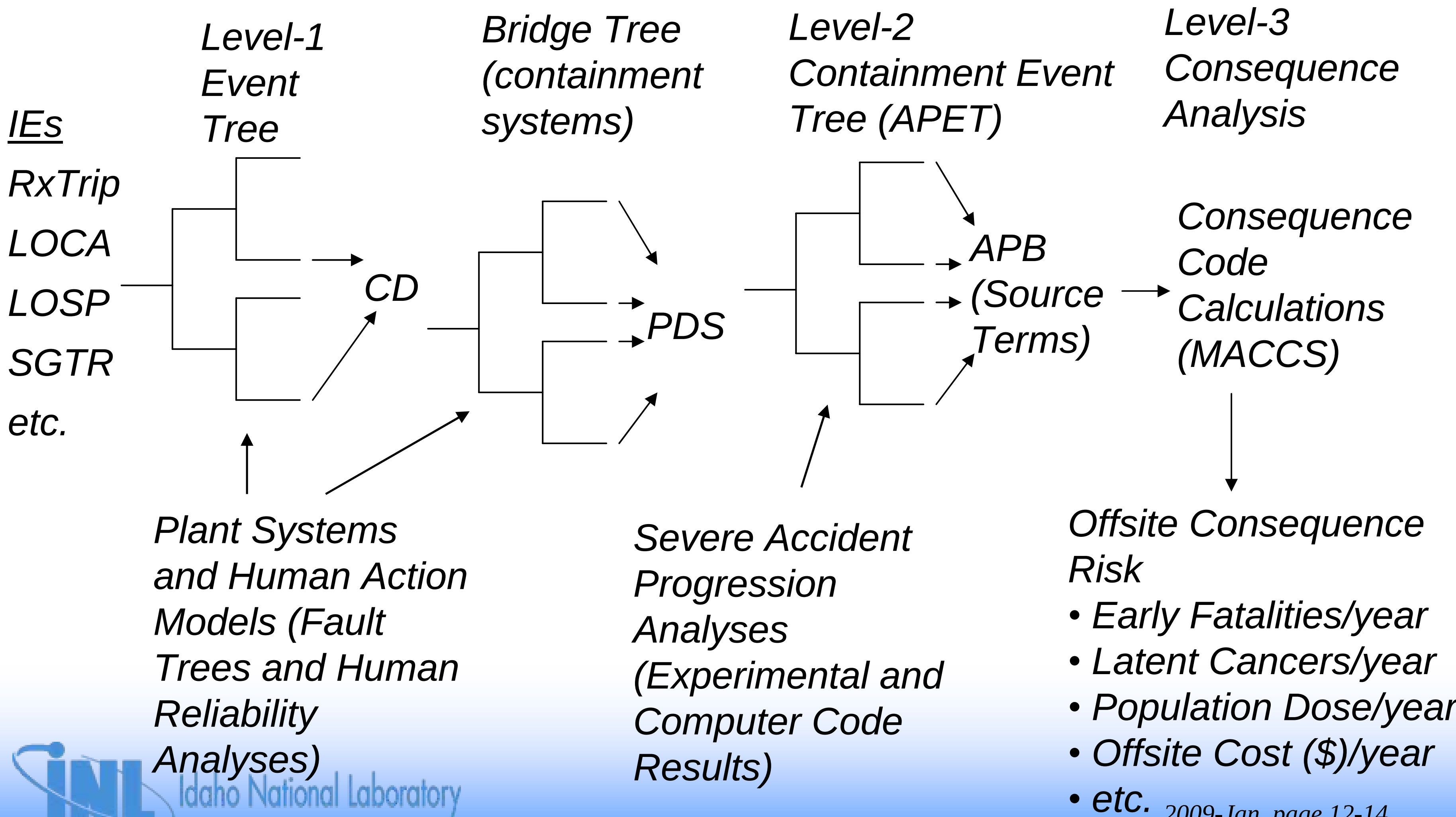
Palisades IPE PDS Char. #’s 2, 3 & 4

2	***Core Damage Timing***
E	*Early CD*
L	*Late CD*
3	***Secondary Cooling***
G	*Secondary Cooling Available*
J	*No Secondary Cooling*
4	***Pressurizer PORV***
M	*PORV Available*
N	*PORV Unavailable*

Palisades IPE PDS Char. #5 (Containment Systems)

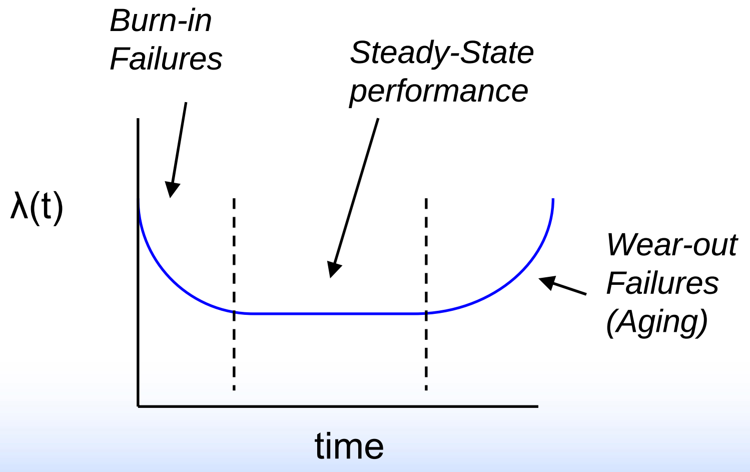
ID	*Description*
P	*Containment sprays and air coolers available*
Q	*Cont. sprays avail. and cont. air coolers NOT avail.*
R	*Only cont. air coolers avail., RWST contents in cont.*
S	*Only cont. air coolers avail., RWST contents NOT in cont.*
V	*No cont. systems avail., RWST contents in cont.*
W	*No cont. systems avail., RWST contents NOT in cont.*
X	*Late (post VB) operation of only HPSI/LPSI*

Overview of Level-1/2/3 PRA



Aging

- Not accounted for in vast majority of PRAs/IPEs
- System is no longer memoryless
  - Violation of Poisson assumption; failure rate is not constant (termed “hazard function”)
    - Failure rate is time dependent



Typical Bathtub Curve

Aging (cont.)

- Given $\lambda(t)$ quantification is straightforward
  - Failure rate changes only affect numerical values in fault tree, not structure
  - Failure rate usually changes slowly enough that time-dependent effects are not important during accident
- Aging is particularly of interest for passive components
  - Active components are maintained and sometimes replaced
  - Passive components are often left out of the analysis because of their initially low failure rates

Aging (cont.)

- Estimation of $\lambda(t)$: some work suggests that a linear aging model is reasonable

  $$\lambda(t) = a + b \bullet t$$

- Alternatively, physical models for component behavior can be used
  - i.e., explicitly accounting for physical aging mechanisms

External Events Analysis

Objective

- **Estimate risk contribution due to "external events"**
- **Events modeled typically include:**
  - **Seismic events**
  - **Area events**
    - **Fires**
    - **Floods (internal and external)**
- **Require detailed plant layout information**

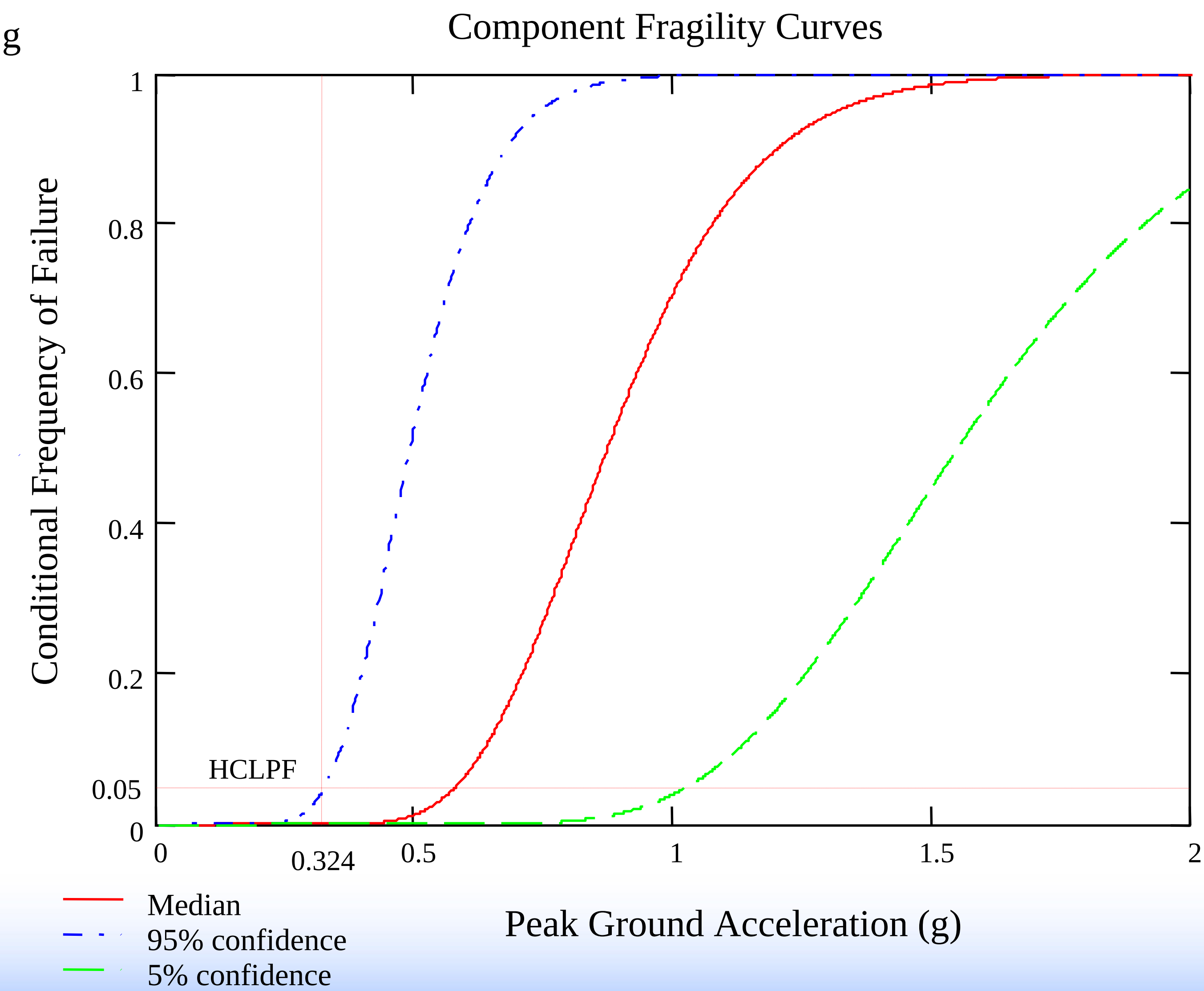
External Events Analysis (Seismic)

- Seismic events analysis requires 3 basic steps
  - Hazards analysis (frequency-magnitude relationship for earthquakes)
  - Fragility analysis ("strength" of components)
  - Accident sequence analysis

$A_m = 0.87$ g

$\beta_r = 0.25$

$\beta_u = 0.35$



External Events Analysis (Area)

- Spatially coupled events analysis requires 4 basic steps
  - Spatial interactions analysis
  - Frequency analysis
  - Damage analysis
  - Accident sequence analysis

System Modeling Techniques for PRA

Appendix A – Workshops

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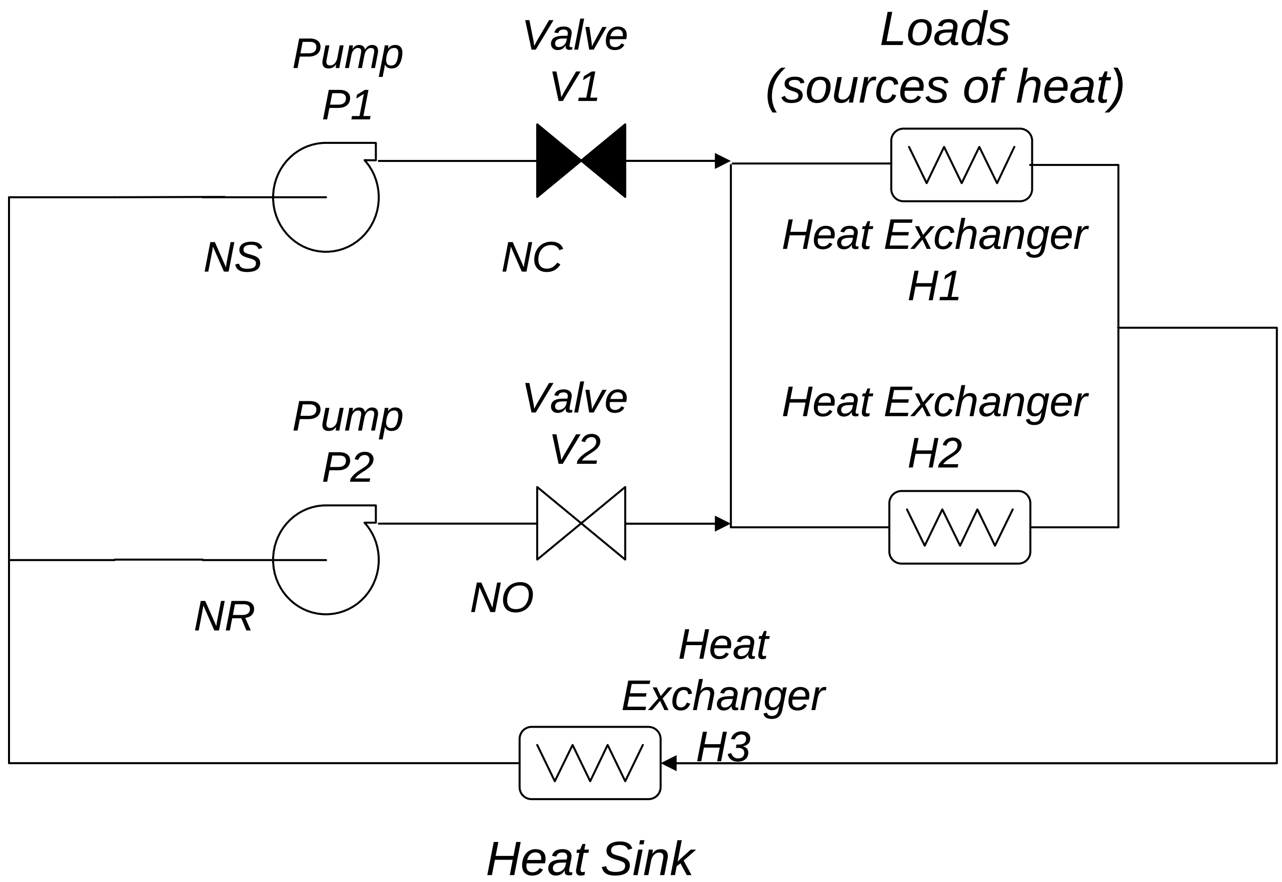
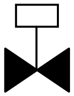
Probability and Frequency

1. An event occurs with a frequency of 0.02 per year.
   1.1. What is the probability that an event will occur within a given year?
   1.2. What is the probability that an event will occur during the next 50 years?
2. Event A occurs with a frequency of 0.1 per year. Event B occurs with a frequency of 0.3 per year.
   2.1. What is the probability that an event (either A or B) will occur during the next year?
   2.2. What is the probability that an event (either A or B) will occur during the next 5 years?
3. An experiment has a probability of 0.2 of producing outcome C.
   3.1. If the experiment is repeated 4 times, what is the probability of observing at least one C?
   3.2. This same experiment has a probability of 0.4 of producing outcome D; however, if C occurs, then the probability of outcome D on the next trial is 0.6 (probability of C remain unchanged at 0.2). If the experiment is repeated (i.e., performed twice), what is the probability of at least one D?

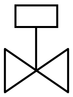
Fault Tree - #1



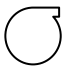
Closed loop cooling system cools loads via heat exchangers H1 and H2. Heat is then remove from system through heat exchanger H3. System successfully performs its function when heat is absorbed through both H1 and H2 , and expelled through H3, with flow maintained by either pump P1 or P2.



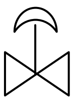
Motor Operated Valve – Normally Closed (requires ac power to operate).



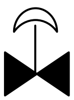
Motor Operated Valve – Normally Open (requires ac power to operate).



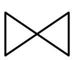
Motor Operated Pump



Air Operated Valve – Normally Open (requires dc power and compressed air to operate, however typically will move to the “safe” position on loss of either).

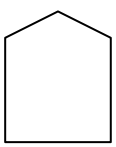


Air Operated Valve – Normally Closed (requires dc power and compressed air to operate, however typically will move to the “safe” position on loss of either).

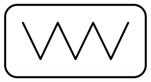


Manually Operated Valve – Normally Open (operates using a hand-wheel or chain-wheel located on the valve itself).

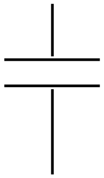
Check Valve – Operates passively, allows flow in only one direction.



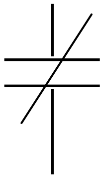
Water Tank – Typically source of water for system



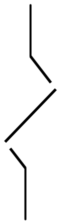
Heat Exchanger – Used to transfer heat from one fluid system to another (i.e., connects two fluid systems in order for one system to cool the other



Electrical contacts or switch - Normally open (i.e., in “off” position)



Electrical contacts or switch - Normally closed (i.e., in “on” position)



Electrical coil or solinoid - Used to operate piece of equipment (e.g., a set of electrical contacts)

NS Normally Stopped

NR Normally Running

NC Normally Closed

NO Normally Open

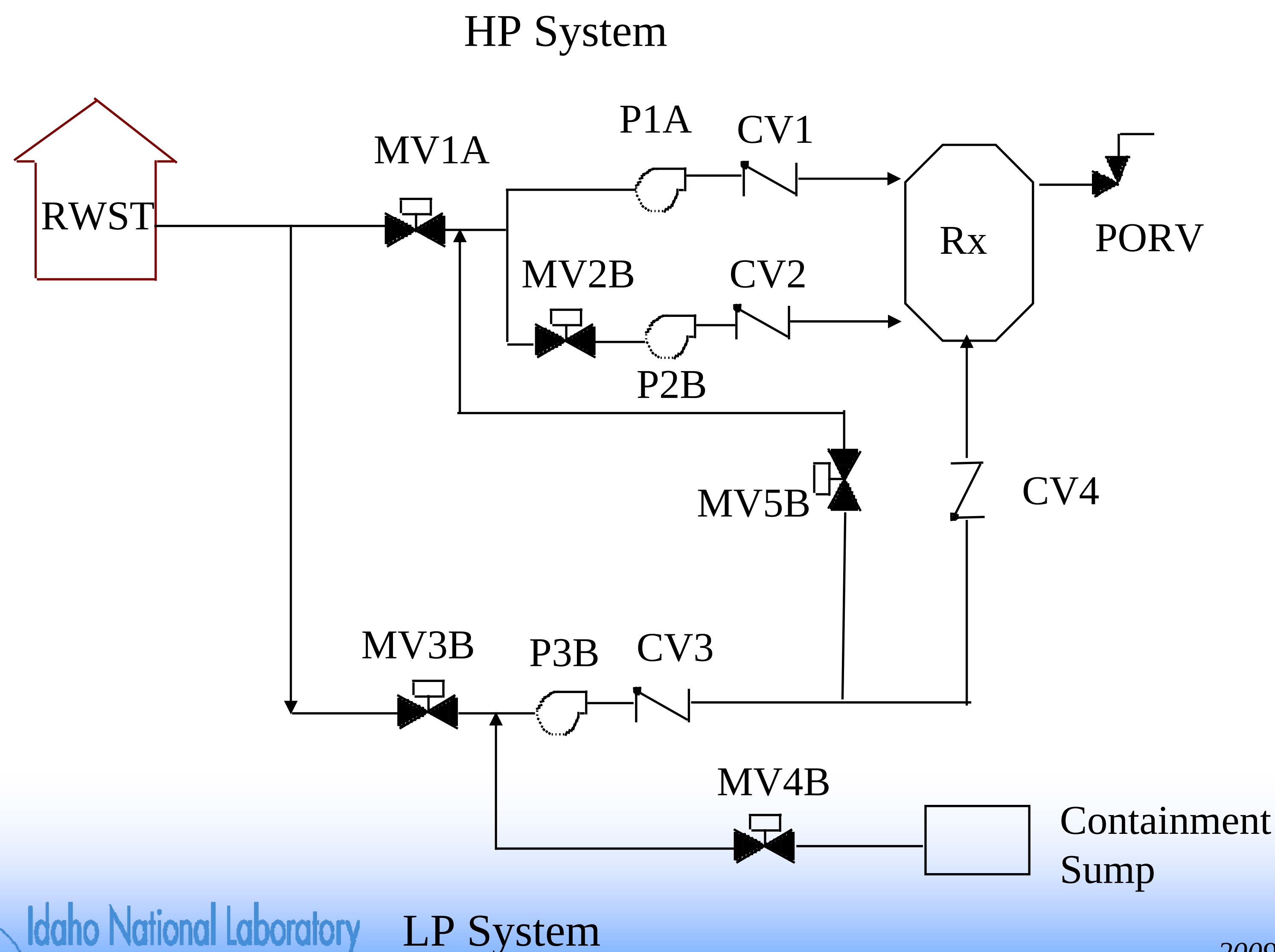
Fault Tree - #2

- **Cooling water pumps have the following support system dependencies:**
  - **AC power**
  - **Room cooling**
  - **Start signal**
- **Pump P1 is normally in standby and must be either automatically or manually started. When the pump is needed to start and run, an automatic actuation signal is sent to the pump. However, if the auto signal fails, the operators can manually start the pump. Also, room cooling is only required during the hot summer months of July and August. The rest of the year, room cooling is not needed. Lastly, the pump is made unavailable for eight hours, twice a year for maintenance.**
- **Successful operation requires the pump to start and run for 24 hours.**
- **Construct a fault tree for P1.**

Data

Component	*Failure Mode*	*Failure Rate*
V - manual valve	**fails to open (FTO)**	**5E-5/demand**
P - motor driven pump	**fails to run (FTR)** **fails to start (FTS)**	**3E-5/hr** **3E-3/demand**
ac – ac power	**loss of power (LOP)**	**1E-7/hr**
rm – room cooling	**loss of room cooling (LOC)**	**1E-6/hr**
H – heat exchanger	**plug (PG)**	**1E-8/hr**
ACT – Actuation	**Manual fails (HE)** **Automatic fails (AU)**	**0.1/demand** **0.01/demand**

Simple Emergency Coolant Injection/Recirculation



Boundary Conditions

- No equipment cooling requirements (room, lube oil, or seal)
- No maintenance of equipment during plant operations, no partial actuation system failures
- “A” components powered from ac bus A
- “B” components powered from ac bus B
- Control power transformed from motive power for all valves (i.e., ignore control power dependencies for valves)
- Control power for pumps provided by respective dc buses, which in turn can be powered from either the same train ac bus or dedicated a battery
- Power operated relief valve (PORV) can be manually opened from control room to depressurize the reactor vessel (Rx) and is powered from dc bus B
- “A” train components actuated automatically by safety injection (SI) signal (powered by dc bus A)
- “B” train components must be manually actuated (from control room)
- If high pressure (HP) system fails, operators can depressurize using PORV and cool reactor using the low pressure (LP) system
- Success criteria for high pressure injection (HPI) is 1 of 2 pumps delivering flow to the reactor vessel (Rx).
- System can operate in a total of four operating modes: HPI, low pressure injection (LPI), high pressure recirculation (HPR), and low pressure recirculation (LPR).
- Ignore heat removal from LPR/HPR water.

Event Tree & Fault Tree Workshop

- Only function required: Provide cooling to reactor vessel (Rx)
- Develop system-level event tree for small loss of coolant accident (SLOCA)
- Generate core damage accident sequence logic
- Develop fault trees for HPI, HPR, LPI and LPR.
- Generate cut sets for HPI, HPR, LPI and LPR.
- Generate core damage sequence cut sets